NAVAL POSTGRADUATE SCHOOL
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THESIS

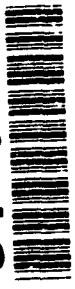
A CAD MODEL FOR THE AXIAL INDUCTIVE STRIP WITH FINITE THICKNESS CENTERED IN HOMOGENEOUS FINLINE WITH w/b=1

by

Dimitris Dariotis

December 1990

Thesis Advisor: Jeffrey B. Knorr



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A Circuit Model for Inductive Strip with Finite Thickness Centered in Homogeneous Finline with w/b=1

by

Dimitrios Dariotis
Lieutenant, Hellenic Navy
B.S., Hellenic Naval Academy, 1982

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December 1990

Author: _____
Dimitrios Dariotis

Approved by: _____
Jeffrey B.Knorr, Thesis Advisor

_____
Ramakrishna Janaswamy, Second reader

_____
Michael A. Morgan, Chairman
Department of Electrical and Computer Engineering

ABSTRACT

This thesis describes a CAD compatible circuit model for an inductive strip with finite metal thickness centered in finline with w/b=1. Scattering coefficients predicted by the circuit model are in good agreement with those predicted by an electromagnetic model based on Maxwell's equations. Filter simulations using the circuit model predict responses which are in good agreement with laboratory measurements.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank Prof. Jeffery B. Knorr for his continued support and guidance. I would also like to thank my wife Tina for her help and moral support and my son Jason-Dimitris for his patience.

I. INTRODUCTION

A. BACKGROUND

It is known from the theory of transmission lines that for efficient transmission, coaxial lines, rectangular waveguides and circular waveguides are usually used. The coaxial line generally is used at frequencies below 5 GHz while rectangular waveguide is used for applications above 5 GHz. Circular waveguides are widely used in situations where the transmitted or received waves are elliptically polarized.

In millimeter wave applications, small sections of transmission lines are often used to realize inductance and capacitance. Microwave integrated circuits for example, are built using planar transmission lines. The importance of millimeter wave systems has increased very quickly during the last twenty years. This importance is more powerful in military applications. Applications such as short range communication with link privacy and precise tracking guidance systems for missiles are improved with the use of the millimeter waves.

Microstrips are often used in the design of microwave integrated circuits to improve the advantages provided by them above 3 GHz. According to Meier [Ref. 1], the advantages include reduced size, production uniformity, reliability, and improved electrical performance. However, integrated circuits at centimeter wavelengths (3-30 GHz) have some fundamental problems which have limited the use of microstrip to fabricate such circuits. The problems are radiation loss, higher mode propagation, and spurious coupling. The above problems become more significant as the operating frequency is raised. To overcome the above problems and other difficulties, integrated finline is often used as a medium for constructing millimeter wave circuits. Figure 1, on page 4 shows a

cross-sectional view of finline, a 3-dimensional view of an inductive strip with finite thickness, and a cross-sectional view of an inductive strip with finite thickness in the waveguide.

The structure of the finline consists of axial metal fins inserted in a rectangular waveguide so that the fin surface is parallel to the narrow waveguide wall. As disadvantages for the integrated finline, we mention that, due to the high field concentration at the edges of the strip, the finline must be used for applications with low and medium power.

Modeling is a powerful capability, the use of which started just recently, to develop microwave computer assisted design (CAD) programs. The goal of CAD programs is to be used as a tool in the design process for microwave circuits. It can be said that such programs are successful if they can predict what one would observe experimentally.

B. OBJECTIVE

The first objective of this research is to measure the scattering coefficients of E-plane inductive metal strips of finite thickness and w/b=1. The second objective is to use measured scattering coefficients to develop a CAD model for the axial inductive strip with finite thickness centered in the finline with w/b=1.

C. RELATED WORK

There have been a number of studies about finline and the inductive strip in finline in the microwave laboratory of NPS. Initially, analysis of the finline using the spectral domain method was published by Knorr and Shayda in 1980 [Ref. 2]. Miller did experimental measurements of scattering coefficients of inductive strips and published data in his thesis in December 1980 [Ref. 3]. A 1981 paper by Knorr presents experimental and numerical data for a shorting septum [Ref. 4]. Experimental and numerical results for

inductive strips were published by Deal in his thesis in March 1984 [Ref. 5], and by Knorr and Deal in October 1985 [Ref. 6]. A 1988 report by Knorr presents a circuit model for an inductive strip centered in a unilateral finline with w/b=1 [Ref. 7]. Lately, a CAD model for inductive strips with infinitesimally thin metal in homogeneous finline was published by Knorr in a March 1990 report [Ref. 8] and by Morua in his thesis work in June 1990 [Ref. 9].

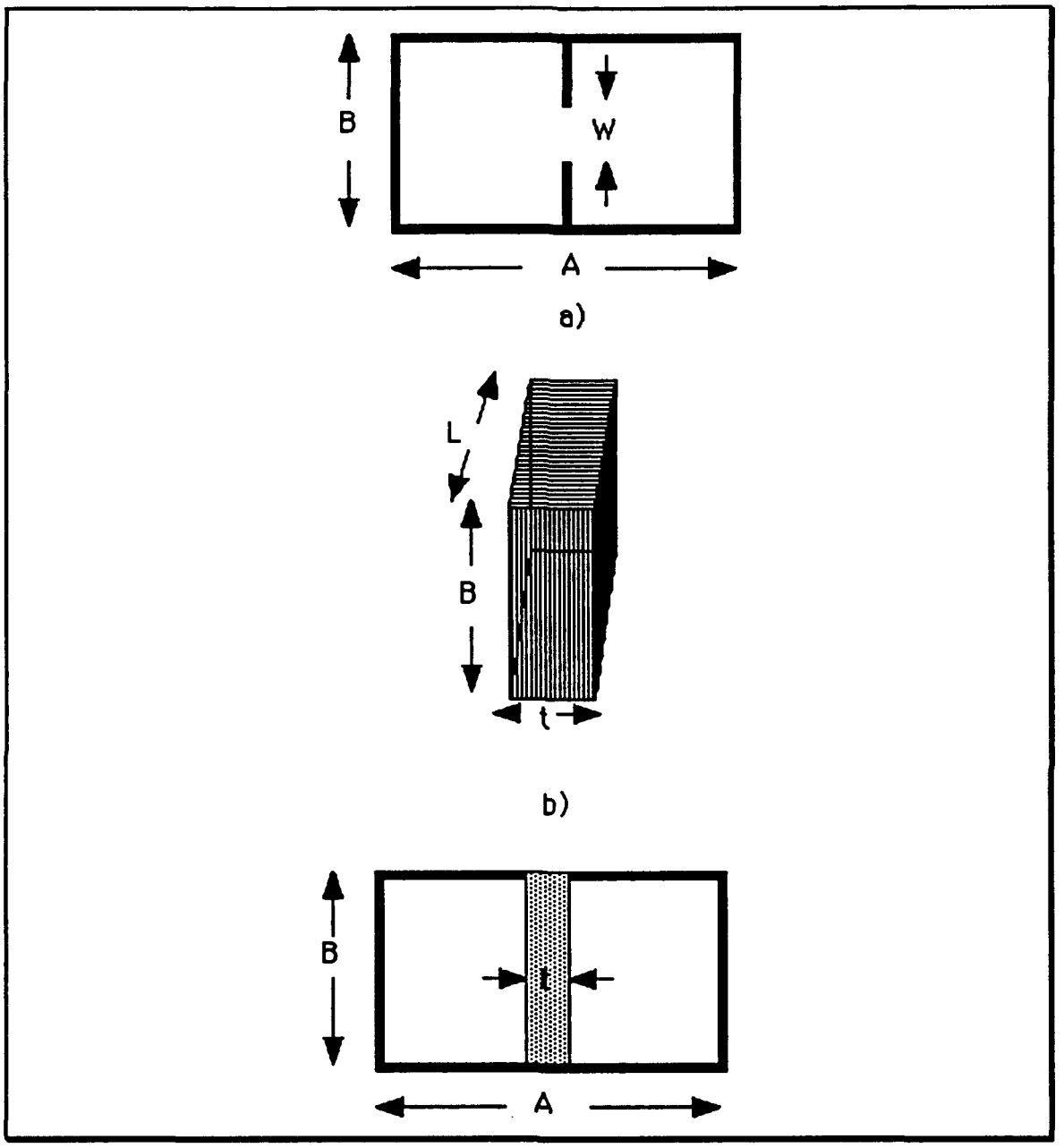


Figure 1. Inductive strip in finline.: a) cross-sectional view of a finline b) inductive strip with finite thickness c) cross sectional view of strip with finite thickness centered in the rectangular waveguide.

II. SCATTERING COEFFICIENTS FOR THE INDUCTIVE STRIP

A. CONCEPT

As mentioned before, the objective of this research is to develop a CAD model for the inductive strip with finite thickness. The already existing models, mentioned above, are for inductive strips with infinitesimally thin metal. The starting point for these models was the scattering coefficients developed by the spectral domain method. The greatest problem of this research was to find a way to measure the scattering coefficients of E-plane inductive strips with finite thickness. At the beginning, with the help of the Mechanical Engineering Department, strips with w/b=1 and strip length t=50, 100, 200 mils were machined. Each of those strips was constructed with thickness t=90, 45 mils and b=400 mils for use with the WR(90) waveguide. However, it was subsequently decided to use the curves of scattering coefficients (|S11|, Θ11) versus strip length for different strip thickness for the Ka band which were published by Yi-Chi Shih in July 1984 [Ref. 10], for the following reasons: a) The dimensions of the machined strips were different than those we requested. b) It was a problem to put the strips into WR(90) waveguide and to center them. c) The generated error of the procedure used to measure the S-parameters. It was also decided that the scattering coefficients measured in the laboratory would be used for validation of Yi-Chi Shih's work [Ref. 10].

B. BACKGROUND

It is known from network theory that in microwave applications it is quite useful to work with the scattering matrix. In our problem, the network has two ports (input, output) which means that the scattering matrix is as follows:

$$S = \begin{bmatrix} S11 & S12 \\ S21 & S22 \end{bmatrix} \tag{1}$$

where S11, S12, S21, S22 are the scattering coefficients of the two-port network.

When the network is lossless and reciprocal, the following equations are valid:

$$|S21| = \sqrt{1 - |S11|^2} \tag{2}$$

$$\Theta 21 = \Theta 11 \pm \frac{\pi}{2} \tag{3}$$

$$S12 = S21 \tag{4}$$

$$|S11| = |S22|. \tag{5}$$

If the network is symmetric, the following equation is valid:

$$\Theta 11 = \Theta 22. \tag{6}$$

If we substitute the above relations into the scattering matrix, we obtain:

$$S = \begin{bmatrix} |S11| e^{j\theta 11} & \sqrt{1 - |S11|^2}\, e^{j[\theta 11 - (2n+1)\frac{\pi}{2}]} \\ \sqrt{1 - |S11|^2}\, e^{j[\theta 11 - (2n+1)\frac{\pi}{2}]} & |S11| e^{j\theta 11} \end{bmatrix}, \; n=0, 1 \tag{7}$$

In this case, the network is assumed to be lossless, reciprocal, and symmetric which means that the scattering matrix is completely determined if the |S11| and $\Theta 11$ are known. We used the curves that Yi-Chi Shih [Ref. 10] published to determine the magnitude and angle of S11 for inductive strips with length T=0.1, 0.2, 0.5, 1, 2, 5 mm. Each of these strips had thickness t=0, 1, 2, 5, 50 mils. In Appendix A there are tables containing the

data and plots of |S11| and Θ11 as a function of frequency for different strip lengths and metal thicknesses. In Appendix A are also included the curves derived from Shih's work [Ref. 10] for the magnitude and angle of the reflection coefficient for inductive strips of thickness t=5 mils centered in the WR (28) rectangular waveguide.

III. A CAD MODEL FOR THE INDUCTIVE STRIP

A. BACKGROUND

It is known that the dominant mode for the rectangular waveguide is the TE10 mode; the E-field exists in the y dimension of the waveguide. When a septum or a strip is put in the waveguide, a potential is generated by the E-field between the upper and lower walls and current flows on the surface of the strip. This results in a storage of magnetic energy. This discontinuity in the rectangular waveguide appears as an inductive reactance.

In a March 1990 report by Knorr [Ref. 8] one can see that a homogeneous finline can be represented by a rectangular waveguide having the same impedance and wavelength. That means, if one measures the finline cut-off wavelength and the impedance, an equivalent rectangular waveguide can be constructed from the following equations:

$$\frac{a_{eq}}{a} = \frac{\lambda_c}{2a} \tag{8}$$

$$\frac{b_{eq}}{b} = \frac{Z_{ov}}{120\pi}\left(\frac{a_{eq}}{a}\right)\left(\frac{a}{2b}\right) \tag{9}$$

where, λ_c and Z_{ov} are the cut-off wavelength and the impedance of the homogeneous finline, a_{eq} and b_{eq} are the dimensions of the equivalent waveguide, and a and b the dimensions of the finline. In this research, the finline have w/b=1, where w/b is the ratio of the fin gap to finline height. So, we have: a_{eq}=a and b_{eq}=b.

Knorr describes in his work [Ref. 8] the inductive strip in finline as a strip region, a discontinuity region, and a finline region. The proposed model for the strip region consists

of two sections of below-cut off rectangular waveguides. These two waveguides represent the spaces between the inductive strip and the narrow waveguide walls. In order to take into account the thickness of the inductive strip, the width of each of the above waveguides must be w=a/2-t/2, where a is the finline width and t is the thickness of the strip. The discontinuity region is modeled by using an inductor and a capacitor to take into account the stored electromagnetic energy mentioned above. Finally, the finline region is modeled by using an ideal transformer to model the impedance step from rectangular waveguide (w/b=1) to the finline with w/b<1.

In this case, because the finlines have w/b=1, we do not need to match the unloaded waveguide with the finline using the above transformer because the voltage power impedance of the unloaded waveguide is equal to the voltage power impedance of the finline. Figure 2, on page 10 shows the equivalent circuit for the inductive strip with finite thickness centered in finline with w/b=1.

B. CIRCUIT MODEL

In order to simulate the equivalent circuit model described in figure 2 on page 10, Touchstone software is used. First, data files for strip length T=0.1, 0.2, 0.5, 1, 2, 5 mm were created. The thickness of each of them is t=0, 1, 2, 5, 50 mils. Then a Touchstone program (Figure 3, on page 11) was written for the equivalent circuit using as parameters, the inductance L and the capacitance C.

As Morua discovered in his thesis work [Ref 9], a match between data and model can be achieved by changing only the inductance while the capacitance remains constant. Morua discovered that the capacitance changes only when w/b changes. In this work, the same observation has occurred, and for this reason, the equation for the capacitance that Morua found in his thesis work was used [Ref 9]. Because in this case w/b=1, the capacitance for the WR(28) is constant and is equal C=0.0008297 PF.

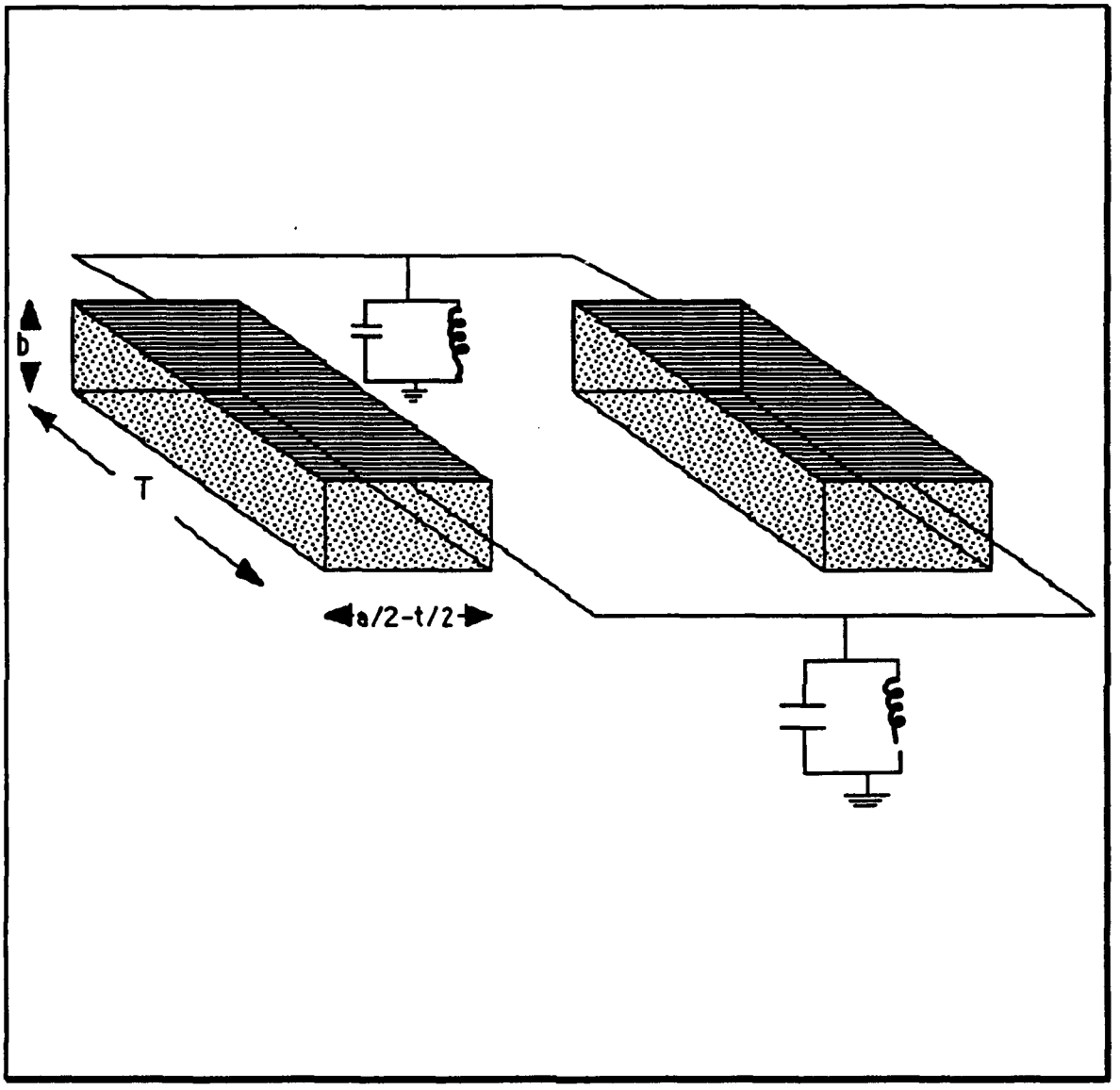


Figure 2. Model for the inductive strip with finite thickness centered in finline with w/b=1.

```
! USER:   DARIOTIS DIMITRIS
! DATE.    SEP-16-90
! CIRCUIT: MODEL FOR THE INDUCTIVE STRIP WITH FINITE METAL
!              THICKNESS CENTERED IN THE FINLINE WITH W/B=1

DIM
  FREQ GHZ
  RES OH
  IND NH
   CAP PF
  LNG MIL
  TIME PS
  COND /OH
  ANG DEG

VAR
    A=280
    B=140
    R=3.3937          !STRIP LENGTH
    t=0               !METAL THICKNESS
    L=5.74
     C=0.0008297
EQN
     Ac=0.5*(A-t)
    Lg=R/2

CKT
   CAP   1   0    C^C
   IND   1   0   L^L
   RWG   1   2    A^Ac  B^B   L^Lg   ER=1    RHO=1
   DEF2P 1   2    D
   D     1   2
   D     1   2
   D     3   2
   D     3   2
   DEF2P 1   3    STRIPA
   S2PA  1   2   0 KA1A.s2p
   DEF2P 1   2    KA1A

   RWGT  1        A=280 B=140 ER=1   RHO=1
    DEF1P  1 WEDGE
TERM
   STRIPA   WEDGE  WEDGE

PROC!

OUT
   STRIPA   S11    SC1
   STRIPA   MAG[S11]  GR1
   STRIPA   ANG[S11]  GR1A
   KA1A     S11    SC2
   KA1A     MAG[S11]  GR1
   KA1A     ANG[S11]  GR1A

FREQ
     SWEEP  26 40  0.5

GRID
     RANGE  26  40   1
```

Figure 3. A Touchstone program for the inductive strip with finite thickness centered in finline with w/b=1.

The values of the inductances that successfully match between model and data are given in Table 1, on page 13. These values are plotted as a function of strip length, keeping constant the thickness t using the Cricket graph program. Figure 4, on page 14 shows the graph of inductance versus strip length for metal thickness t=0, 1, 2, 5, 50 mm. As we can see from Figure 4, all the curves have exponential form. To find a mathematical formula for the inductance, we approach these curves by using the Logarithmic method of the Ckricet Graph software. Figures 5 and 6, on page 15 show two examples of the above method for inductive strips with thickness t=5, 50, mils.

It can be observed that all the mathematical formulas that approach the curves of inductance versus strip length for constant thickness, have the following shape:

$$L = A_1 - A_2 \log T \tag{10}$$

where A_1 and A_2 are real numbers and T is the strip length. In Table 2 on page 13 the values of the above coefficients are given for different metal thicknesses.

To find a general formula for the inductance for all the strip lengths and thicknesses, one must find mathematical expressions for the above two coefficients A_1 and A_2. First, plot the values of the A_1 and A_2 versus the strip thickness and then use two different methods to approach these curves. Shih's curves [Ref. 10] were for metal thickness t=0, 1, 2, 5, 50 mils. As can be seen, there are only 5 points and the last two (5, 50) were very far from each other. That is the reason (in order to be more accurate), two methods were used. The first method utilized the Matlab software. The coefficients A_1 and A_2 were plotted versus thickness and then the Fitfun application of the Matlab was used in order to approach the curves. The second was made with the help of the best fit software of the Hewlett Packard computer. In Figures 7 and 8, on page 16 we can see these methods.

The dotted line represents the plot of data, (five points) the continuous line is the Matlab result and the dashed line is the HP result.

TABLE 1. INDUCTANCE (nH) FOR BEST MATCH BETWEEN MODEL AND SHIH'S DATA

	t=0 mils	t=1 mils	t=2 mils	t=5 mils	t=50 mils
T=0.1 mm	7.65	7.18	6.75	5.8	2
T=0.2 mm	7.15	6.7	6.2	5.5	1.95
T=0.5 mm	6.3	5.9	5.6	5	1.65
T=1 mm	5.8	5.4	5.2	4.6	1.45
T=2 mm	5.5	5.1	4.9	4.3	1.3
T=5 mm	4.9	4.7	4.6	3.9	1.2

TABLE 2. COEFFICIENTS A1, A2 FOR THE INDUCTANCE

Thickness, t (mils)	A1	A2
0	8.4682	1.5881
1	7.9040	1.4628
2	7.3052	1.2438
5	6.4280	1.1130
50	2.3258	0.5354

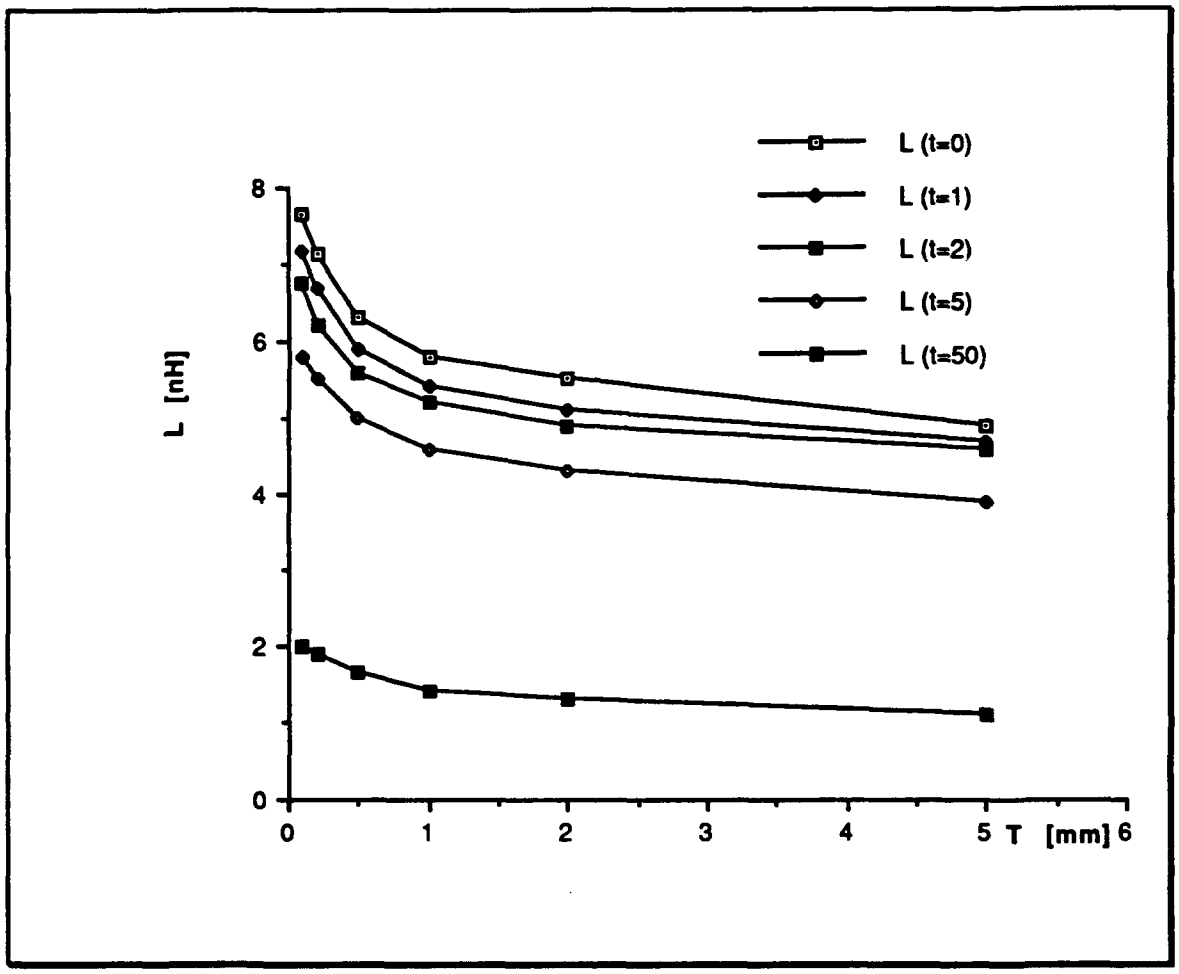


Figure 4. Inductance versus strip length for metal thickness t=0, 1, 2, 5, 50 mils.

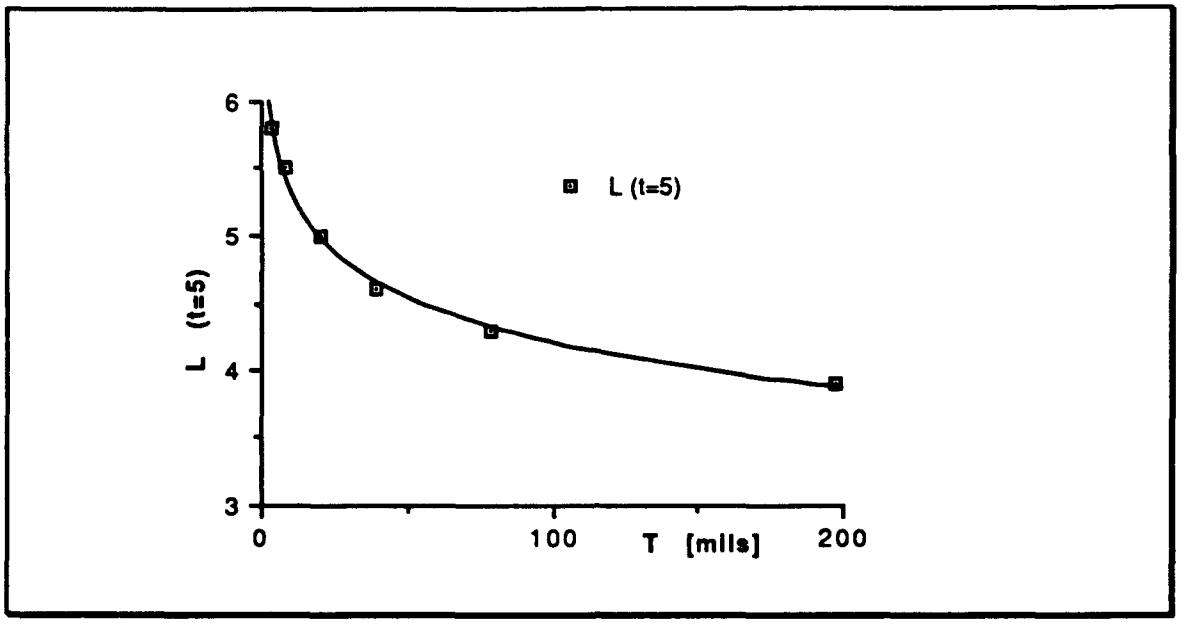


Figure 5. Inductance versus strip length with metal thickness t=5 mils.

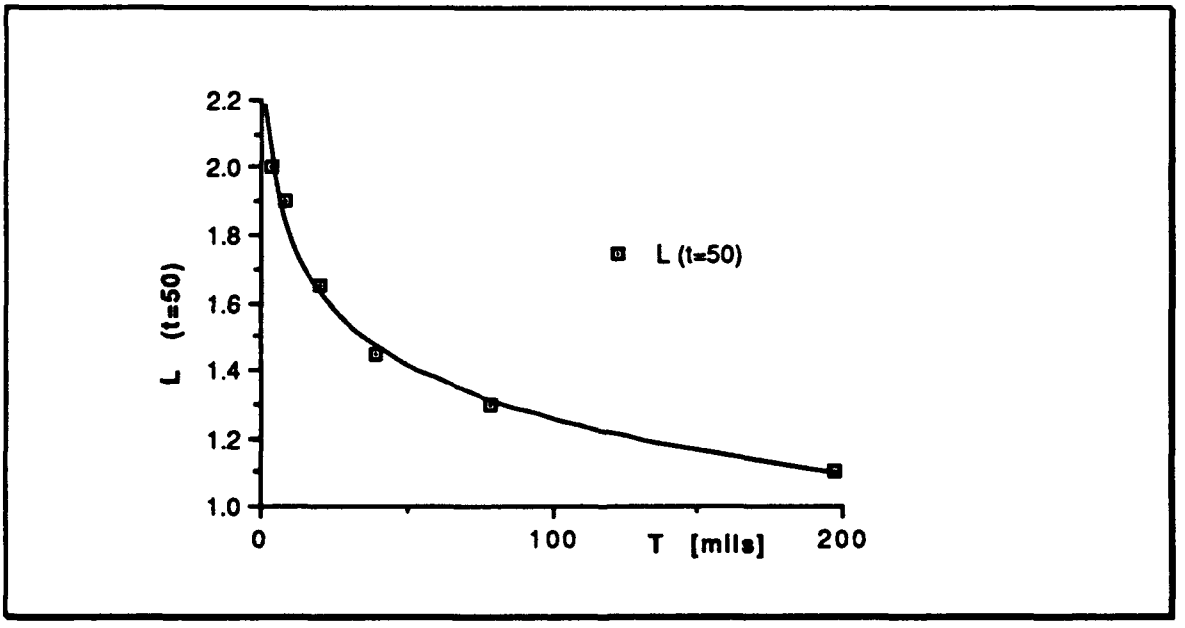


Figure 6. Inductance versus strip length with metal thickness t=50 mils.

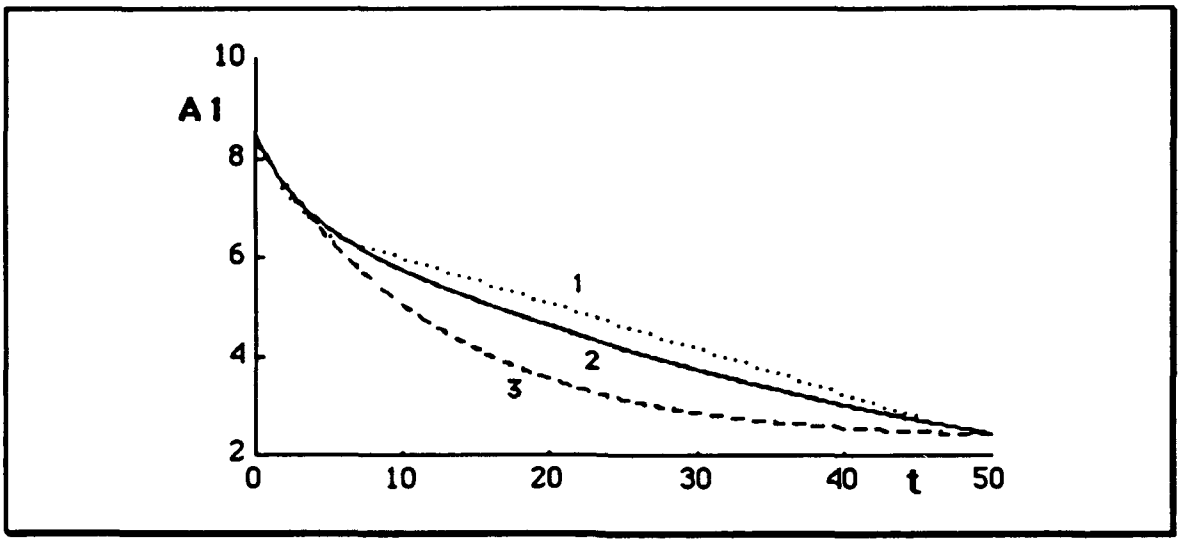


Figure 7. Coefficient A1 versus metal thickness: 1) plot of data 2) Matlab approximation 3) Hewlett Packard approximation.

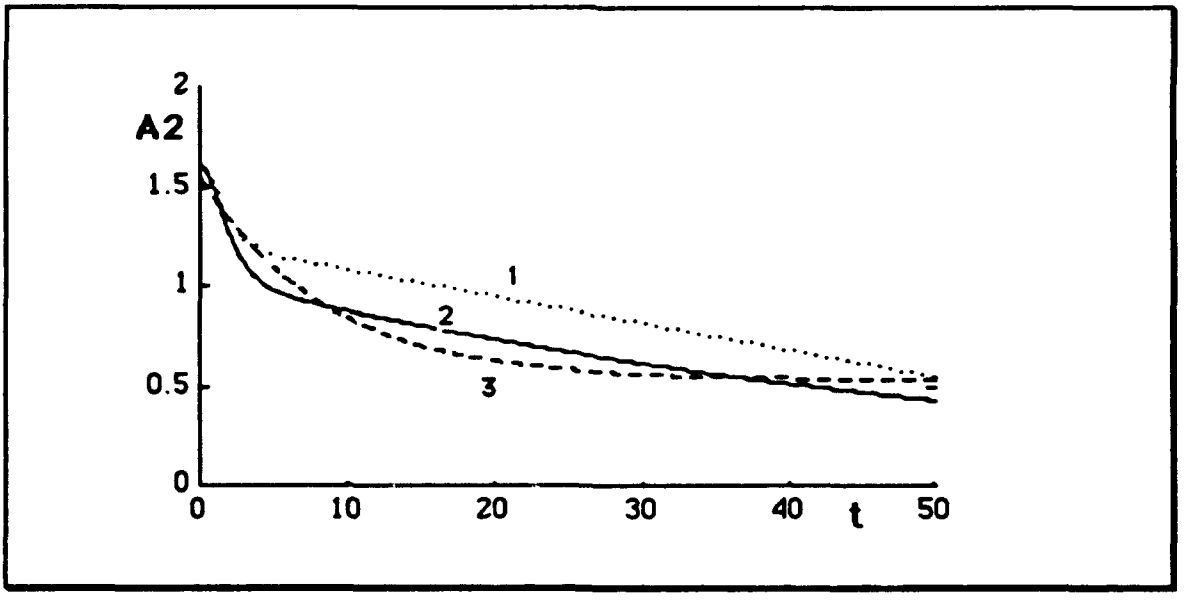


Figure 8. A2 coefficient versus metal thickness: 1) plot of data 2) Matlab approximation 3) Hewlett Packard approximation.

As observed, for both of the coefficients the HP approach is closer to the exponential form. For this reason, this method was chosen to define the coefficients A_1 and A_2. The formulas for the coefficients A_1 and A_2 given by the above method are:

$$A1 = 2.3258 + 6.0338\, e^{-0.0797\, t} \tag{11}$$

$$A2 = 0.53542 + 1.0103 e^{-0.1197\, t}. \tag{12}$$

If we substitute (11) and (12) in the general formula for the inductance, we have:

$$L = 2.3258 + 6.0338\, e^{-0.0797\, t} - [0.53542 + 1.0103 e^{-0.1197\, t}] \log(T) \quad \text{nH.} \tag{13}$$

where the strip length T, and thickness, t, are in mils.

To see the result obtained by using the general formulas for the inductance and capacitance, a Touchstone file was created, using these formulas (Figure 9) on page 18 and the obtained values of magnitude and angle were compared to the values from Shih's curves [Ref. 10]. Appendix B, contains some plots of magnitude and angle as well as the corresponding Smith chart diagrams comparing model predictions with Shih's data.

C. SCALING THE MODEL FOR ALL THE FREQUENCY BANDS

The developed model works only in the Ka band because the scattering data which are used to define the model, were computed in the Ka band. In order to modify the model to work for any frequency, the scaling method described by Knorr in his March 1990 report [Ref.9] was used. The scaling principle states that if all dimensions and wavelength are scaled by the same factor, the electrical performance will remain unchanged. Using this method, the two general equations for the inductance and capacitance are modified as:

$$L = (\frac{b}{140}) f_1 (\frac{280T}{a}) \text{ nH} \tag{14}$$

$$C = 0.5 (\frac{a}{b}) (\frac{a}{280}) 0.0008297 \text{ pF} \tag{15}$$

where a, b, t, and T are in mils and f_1 is the analytic expression for the inductance of a strip centered in the WR(28) waveguide. Figures 9 and 10 give a Touchstone program for the model that works for all the frequency bands.

```
! USER:     DARIOTIS DIMITRIS
! DATE:     SEP-16-90
! CIRCUIT: MODEL FOR THE INDUCTIVE STRIP WITH FINITE METAL
!           THICKNESS CENTERED IN THE FINLINE WITH W/B=1

DIM
 FREQ GHZ
 RES OH
 IND NH
 CAP PF
 LNG MIL
 TIME PS
 COND /OH
 ANG DEG

VAR
   A=280
   B=140
   R=3.3937
   t= 0
!  L=5.74
   C=0.0008297
EQN

   Ac=0.5*(A-t)
   Lg=R/2
```

Figure 9. A CAD model for the finline for all the frequency bands.

```
    D1=(2.3258+6.0338*EXP(-0.0797*280*t/A))*B/140
    D2=(0.53542+1.0103*EXP(-0.1197*280*t/A))*B/140
!   FORMULA FOR THE INDUCTANCE

    L=D1-D2*LOG(280*R/A)

CKT
!   STRIP #1
    CAP   1   0    C^C
    IND   1   0    L^L
    RWG   1   2    A^Ac  B^B   L^Lg   ER=1   RHO=1
    DEF2P 1   2    D
    D     1   2
    D     1   2
    D     3   2
    D     3   2
    DEF2P 1   3    STRIPA
    S2PA  1   2  0 KA1A.s2p
    DEF2P 1   2    KA1A

    RWGT  1        A=280 B=140 ER=1  RHO=1
    DEF1P 1 WEDGE
TERM
    STRIPA  WEDGE WEDGE

PROC!

OUT
    STRIPA  S11   SC1
    STRIPA  MAG[S11] GR1
    STRIPA  ANG[S11] GR1A
    KA1A    S11   SC2
    KA1A    MAG[S11] GR1
    KA1A    ANG[S11] GR1A

FREQ
    SWEEP 26 40 0.5

GRID
    RANGE 26 40  1
    GR1   0  1   .1
    GR1A  90 180 10
```

Figure 10. A CAD model for the finline for all the frequency bands (cont.).

D. MODEL ACCURACY

An error function is used to define the accuracy of the model. As error function we define:

$$\text{Error} = \frac{|\text{Model value} - \text{Computed value}|}{\text{Computed value}} \times 100$$

The above formula is used to compare Shih's data [Ref. 10] with the data generated by the model. In Appendix C, there are tables that give the values of the error function for the worst cases using inductives strips with lengths T=0.1, 0.2, 0.5, 1, 2, 5 mm and thickness for each of them t=0, 1, 2 ,5, 50 mils. As we can see, in these tables we have about 9% worst error at the edges of Ka band only when the strip length T is smaller than 0.1 mm and the thickness t is smaller than 1 mil. For greater values of thickness and strip length, the worst error is about 1.5%.

Another problem about accuracy, is how accurate are Shih's curves [Ref. 10] that were used to determine the scattering coefficients to develop the CAD model for the inductive strip. As mentioned before, strips that were machined with the help of the Mechanical Engineering department, were used to validate Shih's curves. In figures 11 and 12 Shih's data is compared with the laboratory measured data in X band, for inductive strips with strip length T=200 mils and thickness t=45 mils. Because Shih's work was in the Ka band (26-40 GHz) it was necessary to convert the Ka band data to X band with the scaling method that is mentioned above.

Another method to examine the accuracy of Shih's data used to build the CAD model, is to compare |S11|, Θ11 generated by this model for a finline with zero strip metal thickness and w/b=1 to the data generated by Morua's CAD model [Ref.9] for the same

finline which was based on the spectral domain data. In Appendix C two comparisons for the magnitude |S11|, and angle Θ11 are shown. In the first case, the strip has length T=30 mils in WR(8) and in the second case, the strip has length T =15 mils in WR(28). In Appendix C also, there are tables containing the scattering data generated by the CAD model and spectral domain method. As a result from all the above comparisons, we can say that the data generated by the model are very close to the X band data derived from Shih's work and to the spectral domain data.

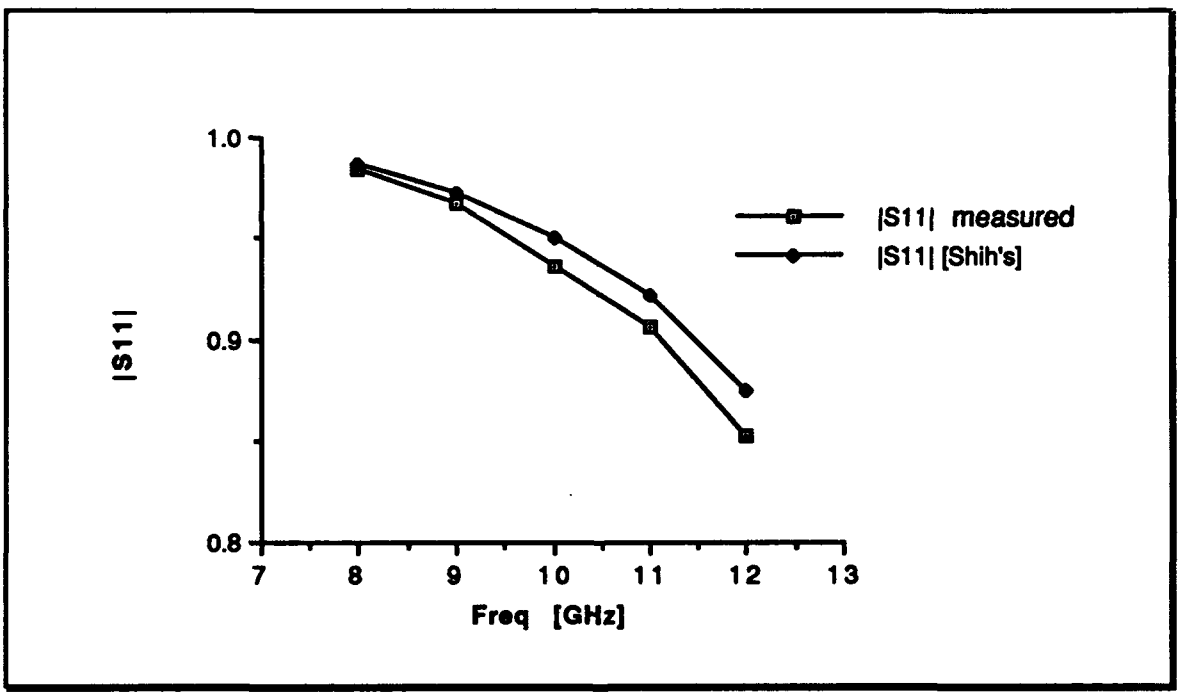


Figure 11 Magnitude |S11| versus Frequency for the measured and Shih's data in the X band for T=200 mils and t=45 mils.

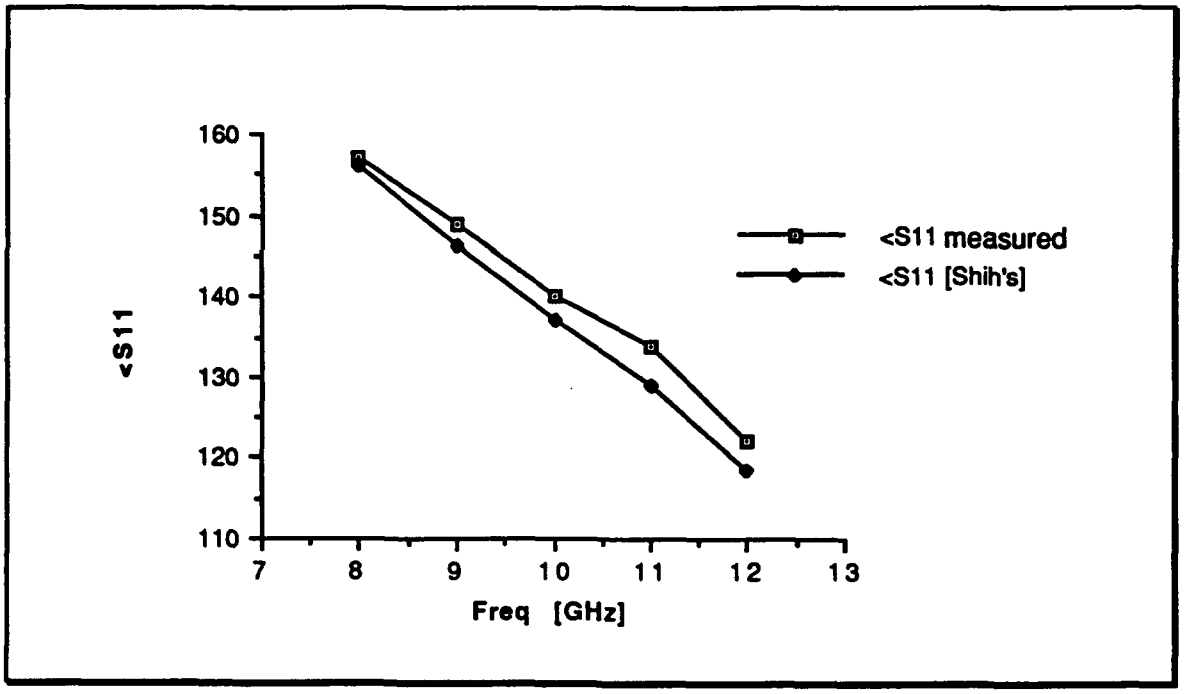


Figure 12. Phase versus Frequency for the measured and Shih's data in the X band for T=200 mils and t=45 mils.

IV. EXPERIMENTAL VALIDATION

The most accurate method to validate the CAD model is to compare the results obtained from the model to what was observed experimentally. In order to do that, a filter was used, which already exists in the NPS laboratory and works in the X band having four inductive strips i.e, three resonators (Figure 13). The dimensions of this filter are T1=90, T2=250, T3=240, T4=90 mils, R1=558, R2=540, R3=540 mils and metal thickness t=2 mils, where, R1, R2, R3 are the distances between the inductive strips. In order to validate the model, a Touchstone circuit file was created for a filter having three resonators; this file is shown in Figures 14, 15, and 16. In Figure 17, one can see the measured filter response. Figure 18 gives the predicted response of the finline filter model which has the same dimensions as the X band filter.

Additionally, three filters are simulated, the responses of which are given by Vahldieck, et al [Ref.11]. Table 3 gives the specifications of these filters. Figures 19, 21,and 23 show the filter responses obtained by Vahaldieck, et al. Figures 20, 22, 24 show the filter responses predicted by the finline filter model. As shown from all the above comparisons, the model responses agree quite well with the experimental responses.

In order to observe the influence of thickness, Figure 73 and 74 in Appendix C show the filters responses predicted by the finline model for the Ka and E band filters with zero thickness. The comparison of Figures 73 and 20 shows that when the metal thickness is zero, the central frequency of the filter response shifts down 1.5 GHz. for the Ka band filter. Also the comparison of figures 74 and 23 shows that when the metal thickness is zero, the central frequency for the E band filter shifts down 2.4 GHz.

TABLE 3. FILTERS SPECIFICATIONS

Frequency	Thickness	T1=T4	T2=T3	R1=R3	R2
Ku Band	35.43 mils	88.11 mils	350.98 mils	413.54 mils	415.27 mils
Ka Band	20.07 mils	39.72 mils	152.36 mils	188.11 mils	188.58 mils
E Band	3.937 mils	24.13 mils	77.87 mils	75.23 mils	75.47 mils

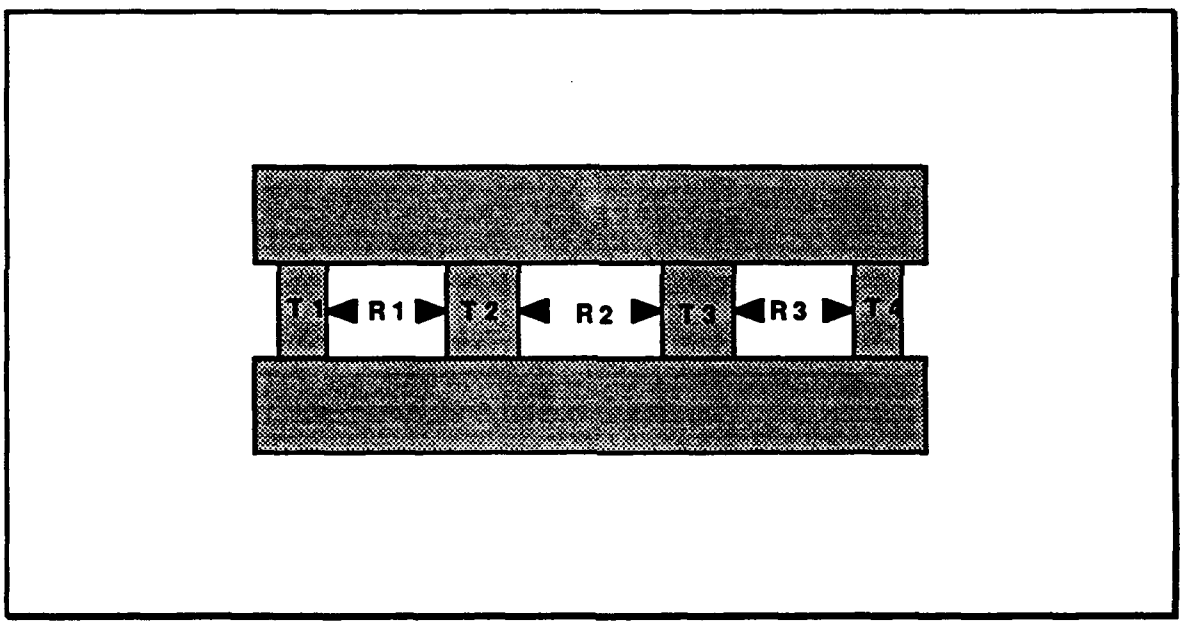


Figure 13. Filter with three resonators.

```
 USER:      DIMITRIS DARIOTIS
! DATE:      JUNE-4-90
! CIRCUIT:  MODEL OF FINLINE FILTER CONSISTING OF FOUR INDUCTIVE
!           STRIPS THREE RESONATORS.STRIPS HAVE FINITE THICKNESS
!           AND ARE CENTERED IN THE WAVEGUIDE WITH W/B=1
! COMMENT: THIS MODEL WORKS FOR ALL FREQUENCY BANDS. TO
           WORK THE MODEL, THE PARAMETERS THAT MUST BE DEFINED
           ARE STRIP LENGTH, METAL THICKNESS DIMENSIONS OF THE
           WAVEGUIDE AND THE OPERATING FREQUENCY.
 DIM
  FREQ GHZ
  RES OH
  IND NH
  CAP PF
  LNG MIL
  TIME PS
  COND /OH
  ANG DEG
VAR
    A=900
    B=400
    k=2.5                    !THICKNESS OF THE STRIP
    T1=90                    !STRIP LENGTH No1
    T2=250                   !STRIP LENGTH No2
    T3=240                   !STRIP LENGTH No3
    T4=90                    !STRIP LENGTH No4
    R1=558                   !DISTANCE BETWEEN STRIPS No1
    R2=540                   !DISTANCE BETWEEN STRIPS No2
    R3=540                   !DISTANCE BETWEEN STRIPS No3
EQN
    Tov2A=T1/2               !MODEL PARAMETERS
    Tov2B=T2/2               !MODEL PARAMETERS
    Tov2C=T3/2               !MODEL PARAMETERS
    Tov2D=T4/2               !MODEL PARAMETERS
    Aov2=0.5*(A-k)
!   FORMULAS FOR THE FACTORS A1 AND A2
    D1=(2.3258+6.0338*EXP(-0.0797*280*k/A))*B/140
    D2=(0.53542+1.0103*EXP(-0.1197*280*k/A))*B/140
!   FORMULAS FOR THE INDUCTANCE
    La=D1-D2*LOG(280*T1/A)
    Lb=D1-D2*LOG(280*T2/A)
```

Figure 14. Finline Filter Model Program.

```
   Lc=D1-D2*LOG(280*T3/A)
   Ld=D1-D2*LOG(280*T4/A)
!  FORMULA FOR THE CAPACITANCE
   C=0.5*(A/B)*(A/280)*0.0008297
CKT
!  STRIP No1
   CAP   1   0    C^C
   IND   1   0    L^La
   RWG   1   2    A^Aov2 B^B  L^Tov2A ER=1  RHO=0.64
   DEF2P 1   2    A
   A     1   2
   A     1   2
   A     3   2
   A     3   2
   DEF2P 1   3    STRIPA
!  RESONATOR No1
   RWG   1   2    A^A   B^B   L^R1   ER=1 RHO=.64
   DEF2P 1   2    RESOA
!  STRIP No2
   CAP   1   0    C^C
   IND   1   0    L^Lb
   RWG   1   2    A^Aov2 B^B  L^Tov2B ER=1  RHO=0.64
   DEF2P 1   2    B
   B     1   2
   B     1   2
   B     3   2
   B     3   2
   DEF2P 1   3    STRIPB
!  RESONATOR No2
   RWG   1   2    A^A   B^B   L^R2   ER=1 RHO=0.64
   DEF2P 1   2    RESOB
!  STRIP No3
   CAP   1   0    C^C
   IND   1   0    L^Lc
   RWG   1   2    A^Aov2 B^B  L^Tov2C ER=1  RHO=0.64
   DEF2P 1   2    C
   C     1   2
   C     1   2
   C     3   2
   C     3   2
   DEF2P 1   3    STRIPC
```

Figure 15. Finline Filter Model program (cont.).

```
! RESONATOR No3
  RWG  1  2   A^A   B^B   L^R3   ER=1 RHO=0.64
  DEF2P 1  2   RESOC
!  STRIP No4
  CAP  1  0   C^C
  IND  1  0   L^Ld
  RWG  1  2   A^Aov2 B^B L^Tov2D ER=1  RHO=0.64
  DEF2P 1  2   D
  D    1  2
  D    1  2
  D    3  2
  D    3  2
  DEF2P 1  3   STRIPD
  RWGT  1      A^A   B^B      ER=1  RHO=1
  DEF1P 1      WEDGE
  STRIPA 1  2
  RESOA 2  3
  STRIPB 3  4
  RESOB 4  5
  STRIPC 5  6
  RESOC 6  7
  STRIPD 7  8
  DEF2P 1  8   FINFILT
TERM
  FINFILT   WEDGE WEDGE
PROC!
OUT
  FINFILT  DB[S11]  GR1
  FINFILT  DB[S12]  GR1
FREQ
   SWEEP 8   12   0.01
   SWEEP 9.7  11.5  0.01
GRID
   RANGE 8   12 0.4
   GR1  -60  20  10
OPT!
TOL!
```

Figure 16. Finline Filter Model program (cont.).

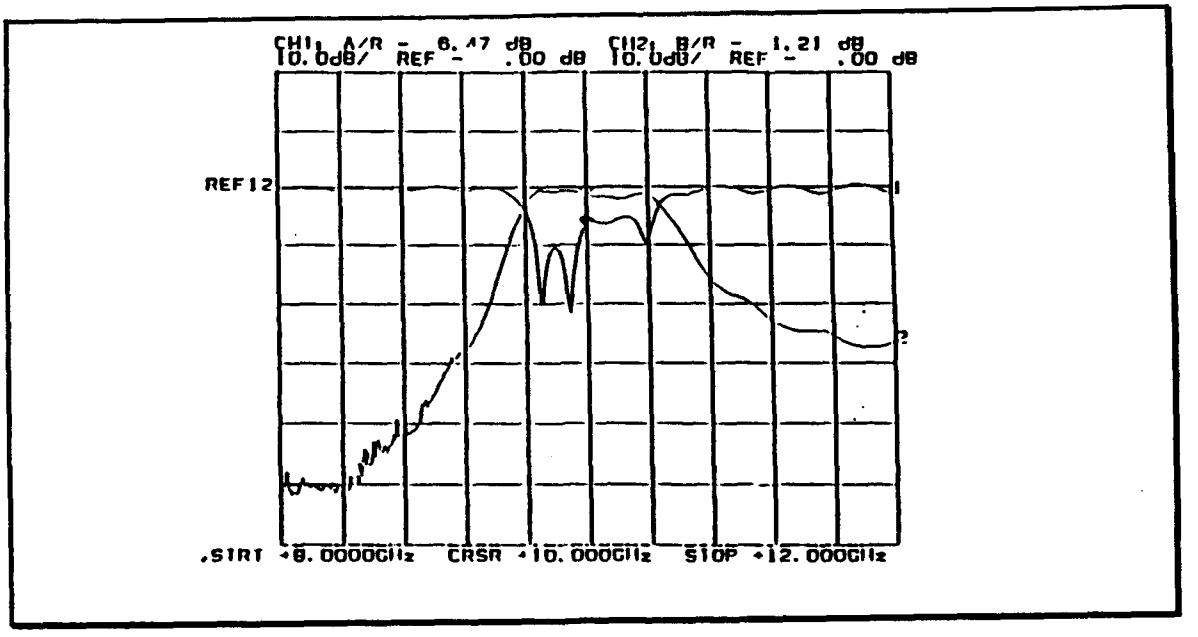


Figure 17. Experimental response for the X-Band filter [Ref 9].

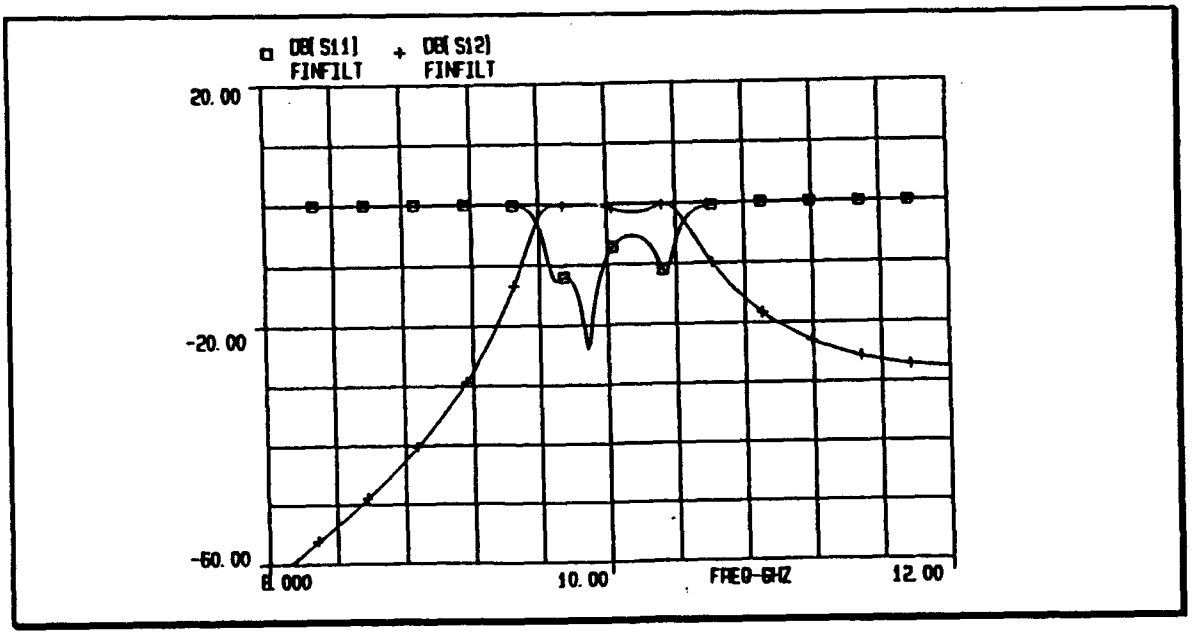


Figure 18. Filter response from the finline filter model Touchstone program.

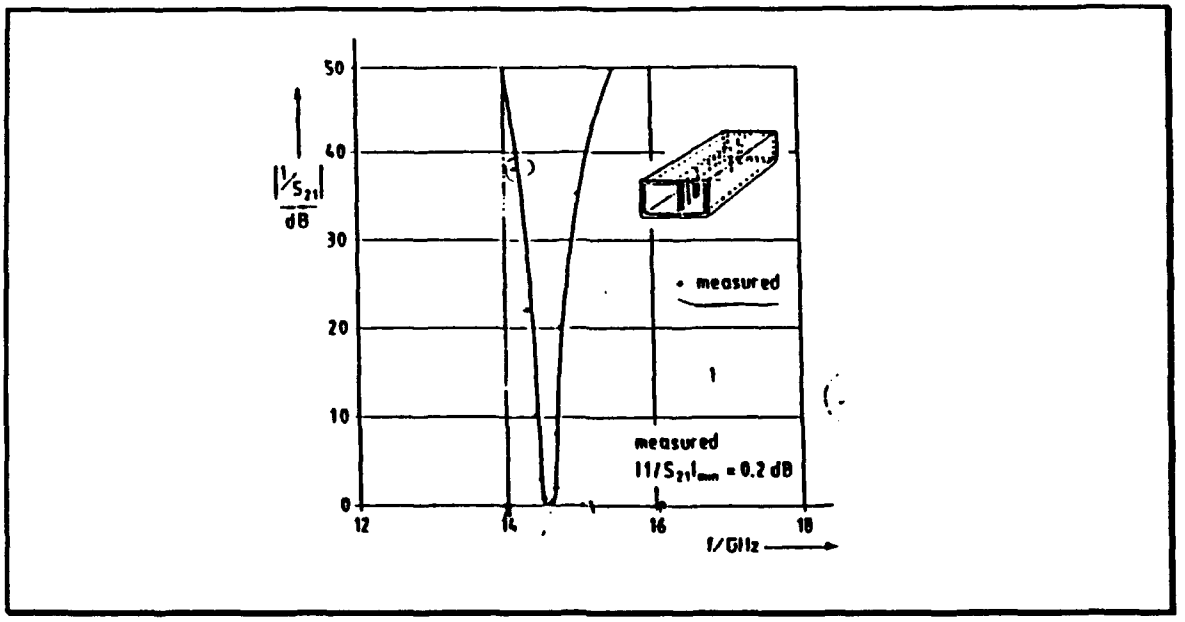


Figure 19. Experimental response for the Ku Band filter [Ref 11].

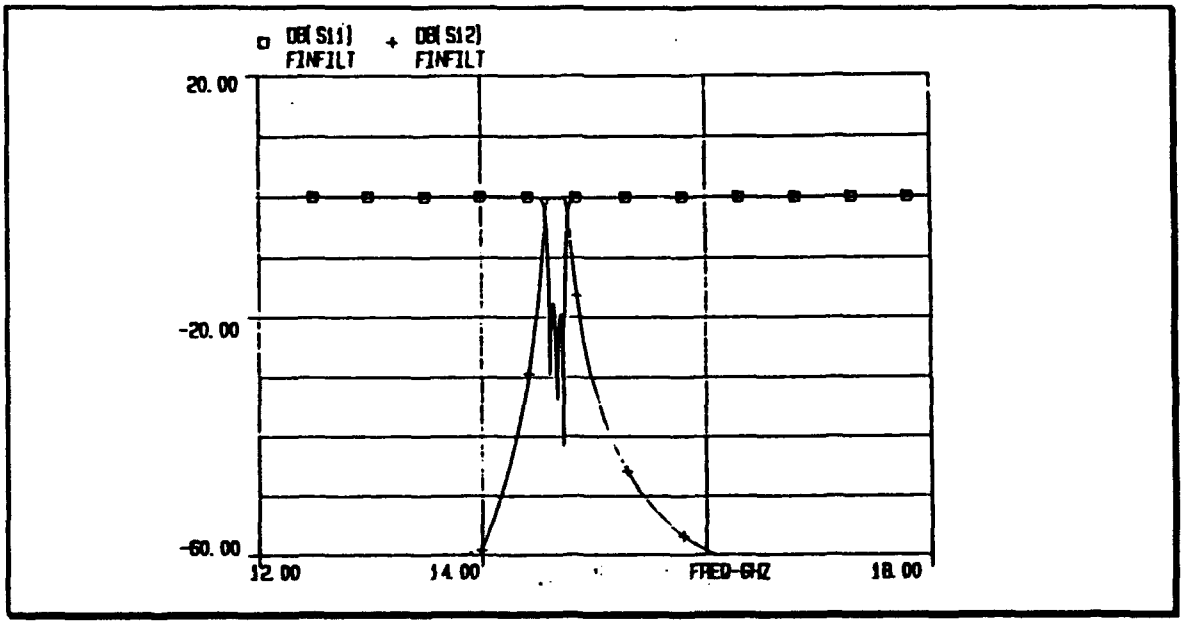


Figure 20. Model response for the Ku Band filter.

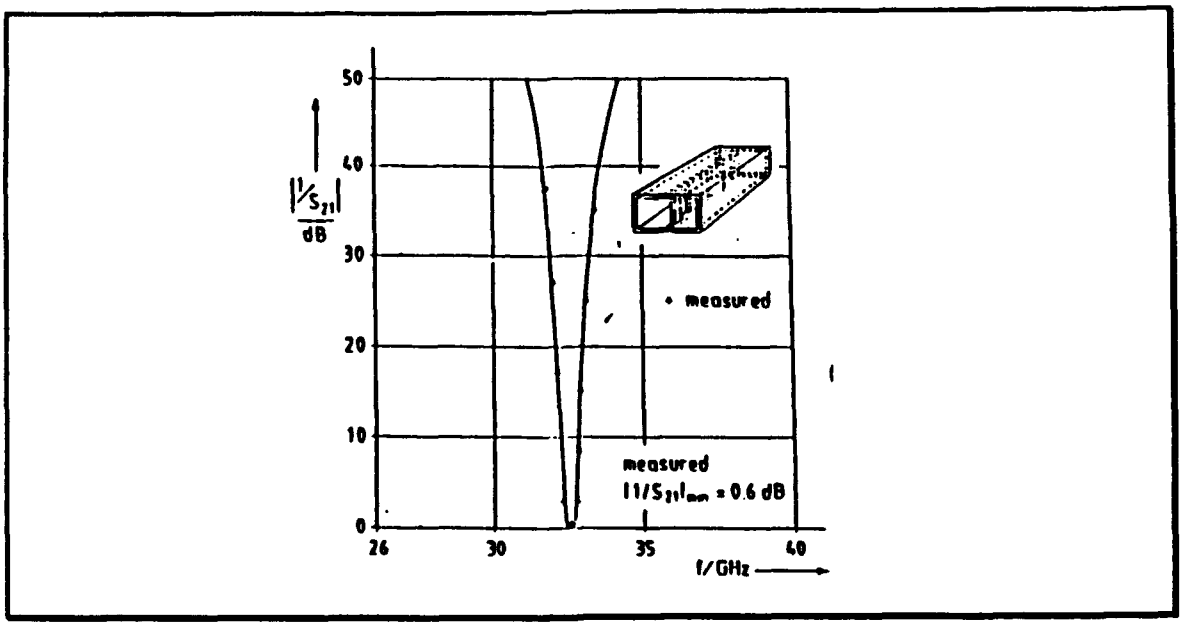


Figure 21. Experimental response for the Ka band filter [Ref 11].

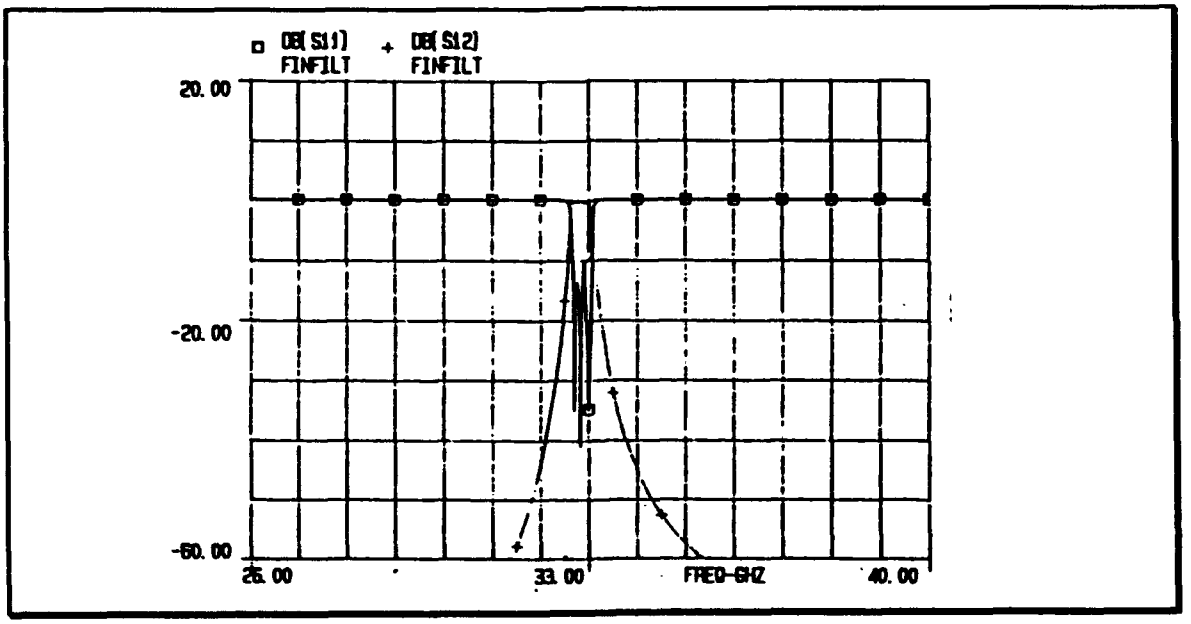


Figure 22. Model response for the Ka Band filter.

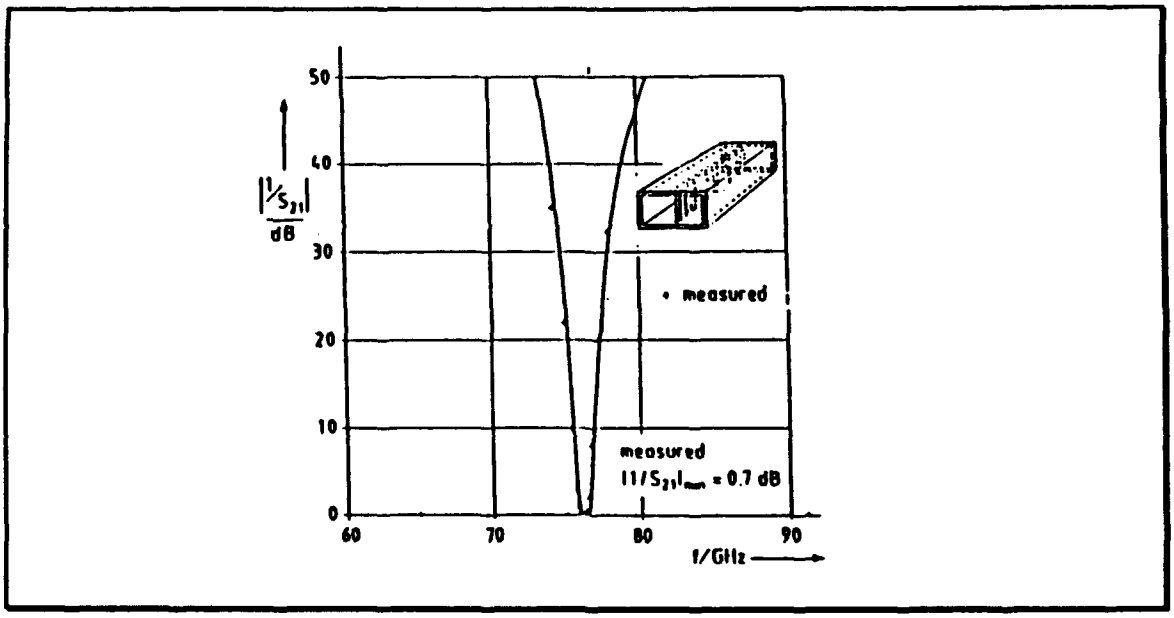


Figure 23. Experimetal response for the E Band filter [Ref 11].

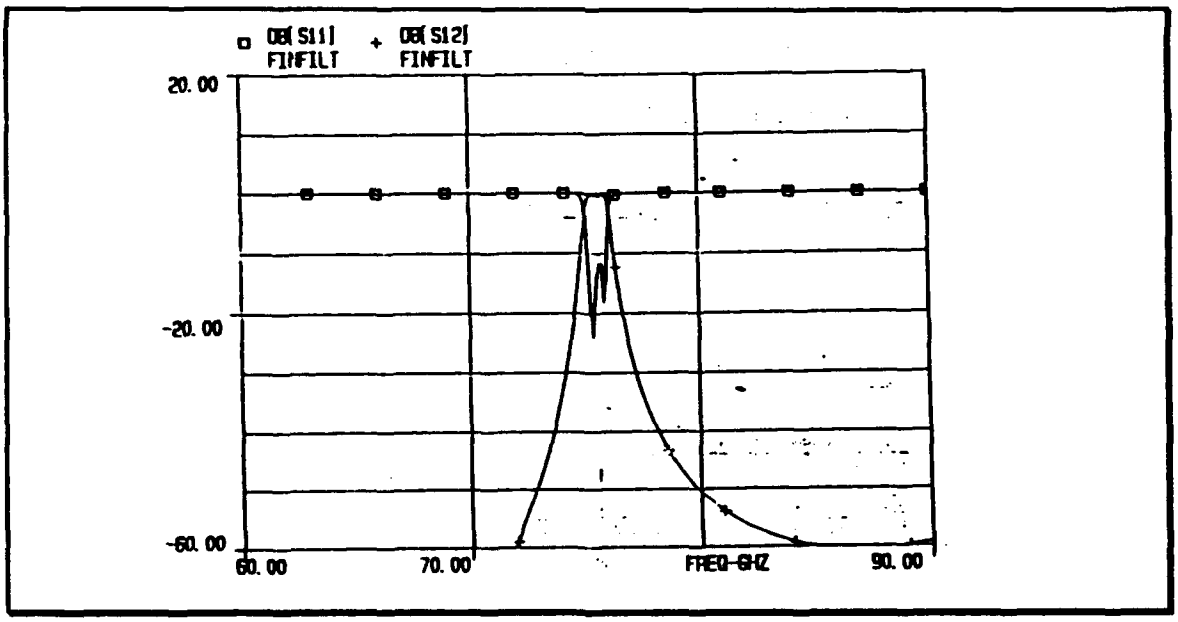


Figure 24. Model response for the E Band filter.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis describes a CAD model for the inductive strip with finite metal thickness which is centered in a finline with w/b=1. The starting point for this model was the curves of magnitude and phase of the reflection coefficient, S11, for inductives strips with finite metal thickness derived from Shih's work for the Ka band [Ref. 10]. The data were in the range $0.01<T/a<0.7$ and $0<t/a<0.17$. As described in the chapters of Model Accuracy and Experimental Validation, Shih's data are very close to the data measured in the laboratory and to the data generated by the spectral domain method as well. Also, the experimental responses of various existing filters were close to the responses predicted by the model. The above agreement leads to the conclusion that the CAD model described here for millimeter wave applications can be used.

B. RECOMMENDATIONS

The successful match of the model results to the results obtained in the laboratory, recommends that the work in the Microwave Department of NPS continue in the following areas:

1. Develop a model for strips centered in finline with $w/b<1$, and finite metal thickness.
2. Develop a model for inductive strips which are off-center with $w/b<1$, and finite metal thickness.
3. Investigate the effect of a dielectric substrate for strips with $w/b<1$, and finite metal thickness.

APPENDIX A. S-DATA

TABLE 4. S-DATA FOR STRIP LENGTH T=0.1 MM.

	t=0 mils		t=1 mil		t= 2 mils		t=5 mils		t=50 mils	
Freq	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11
26	0.641	128.02	0.679	131.36	0.7125	133.75	0.7708	138.53	0.9708	165.28
30	0.504	117.99	0.545	120.85	0.579	123.24	0.6458	127.54	0.9416	159.07
36	0.391	109.39	0.425	111.78	0.450	113.69	0.516	117.51	0.887	150.95
40	0.333	105.57	0.366	107.67	0.391	108.91	0.450	112.73	0.8416	145.22

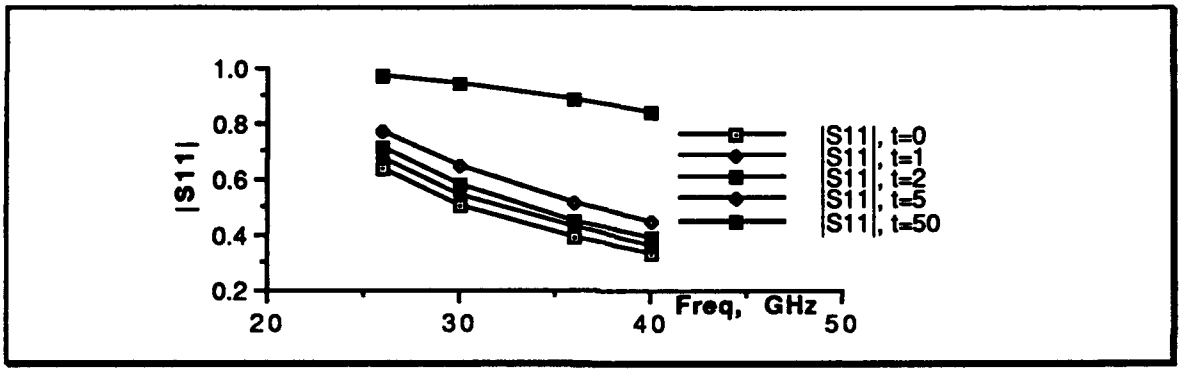


Figure 25. Magnitude of S11 versus frequency for strip length T=0.1 mm

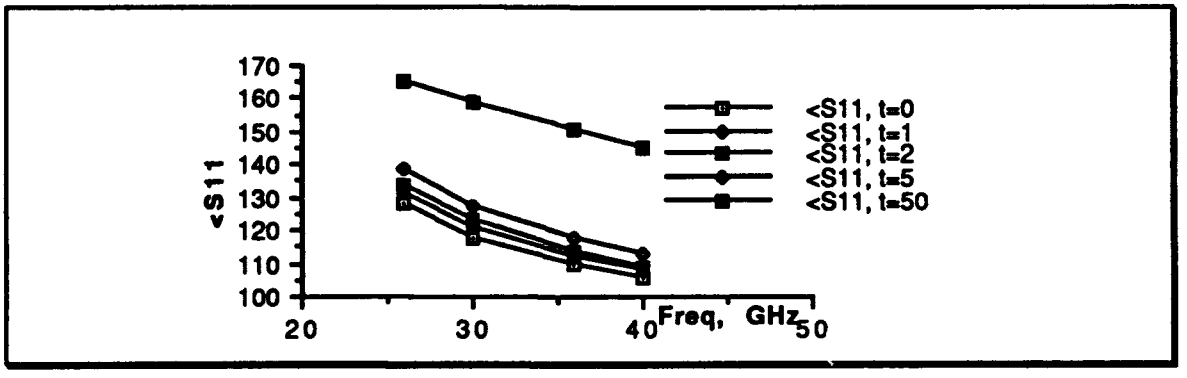


Figure 26. Angle Θ11 versus frequency for strip length T=0.1mm.

TABLE 5. S-DATA FOR STRIP WITH LENGTH T=0.2 MM.

	t=0 mils		t=1 mil		t=2 mils		t=5 mils		t=50 mils	
Freq	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11
26	0.725	133.75	0.754	135.66	0.775	137.57	0.8208	141.40	0.975	166.24
30	0.5958	121.81	0.629	124.20	0.650	126.11	0.704	130.41	0.950	159.55
36	0.466	111.78	0.4958	113.31	0.5208	114.64	0.5708	118.47	0.908	151.43
40	0.408	106.05	0.433	107.96	0.4525	109.15	0.500	112.73	0.866	145.70

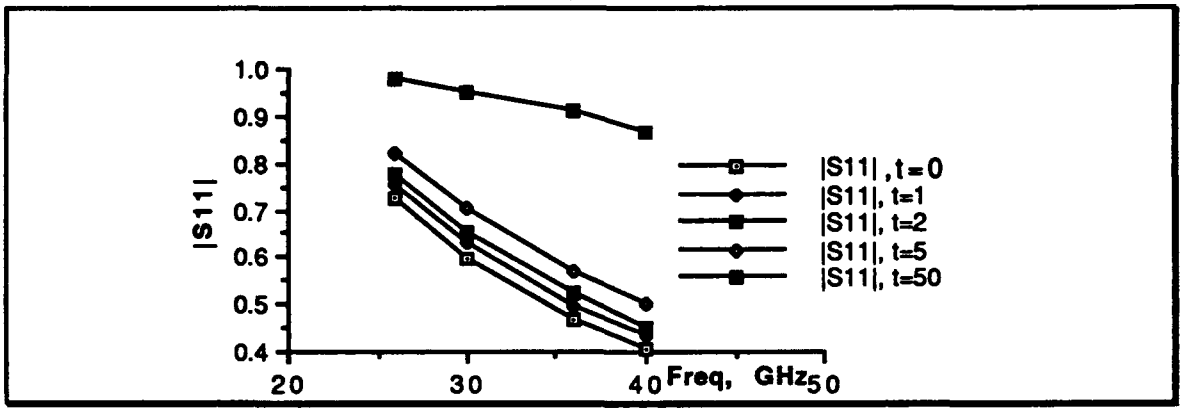


Figure 27. Magnitude of S11 versus frequency for strip length T=0.2 mm.

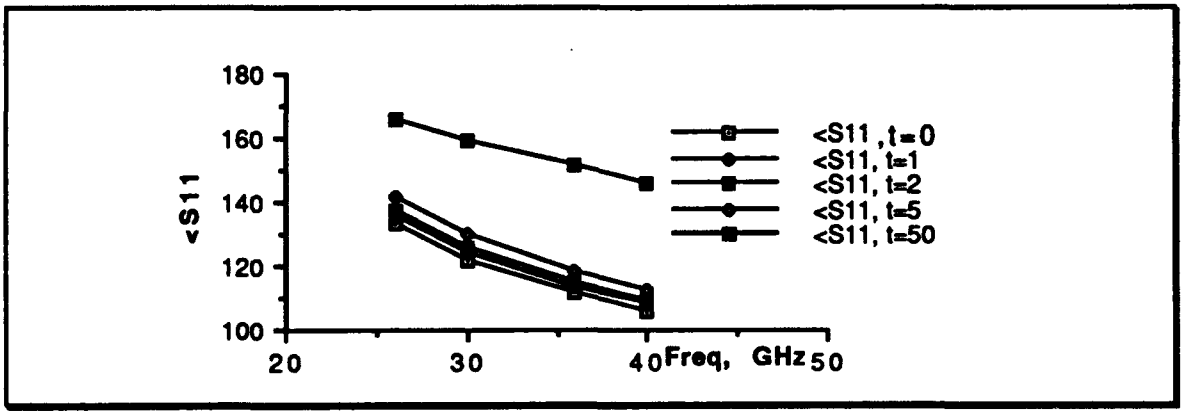


Figure 28. Angle Θ11 versus frequency for strip length T=0.2 mm.

TABLE 6. S-DATA FOR STRIP LENGTH T=0.5 MM.

	t=0 mils		t=1 mil		t=2 mils		t=5 mils		t=50 mils	
Freq	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11
26	0.850	140.44	0.866	141.87	0.875	143.31	0.900	146.65	0.991	166.72
30	0.7458	127.07	0.766	128.69	0.783	130.41	0.816	133.75	0.975	160.50
36	0.625	112.73	0.6375	114.17	0.654	116.08	0.695	119.42	0.95	152.38
40	0.5375	104.61	0.558	106.05	0.575	107.96	0.616	111.30	0.916	146.65

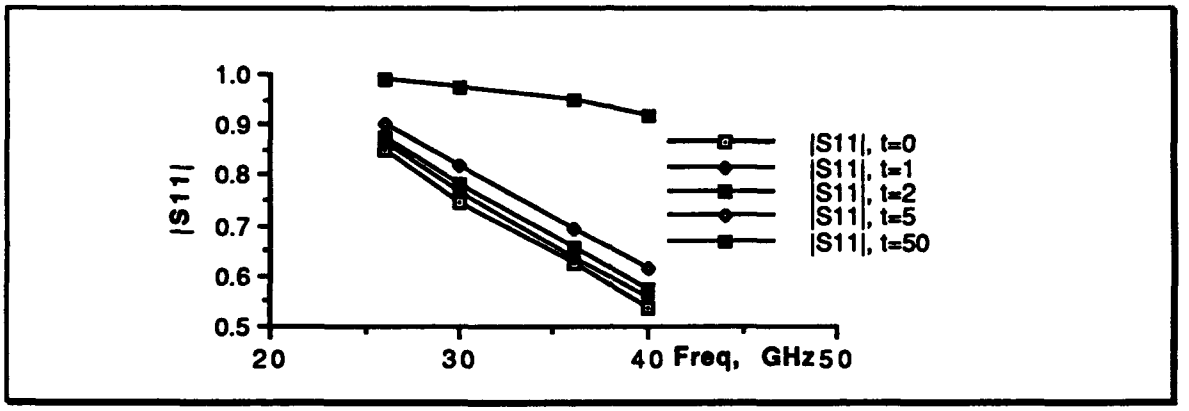


Figure 29. Magnitude of S11 versus frequency for strip length T=0.5 mm.

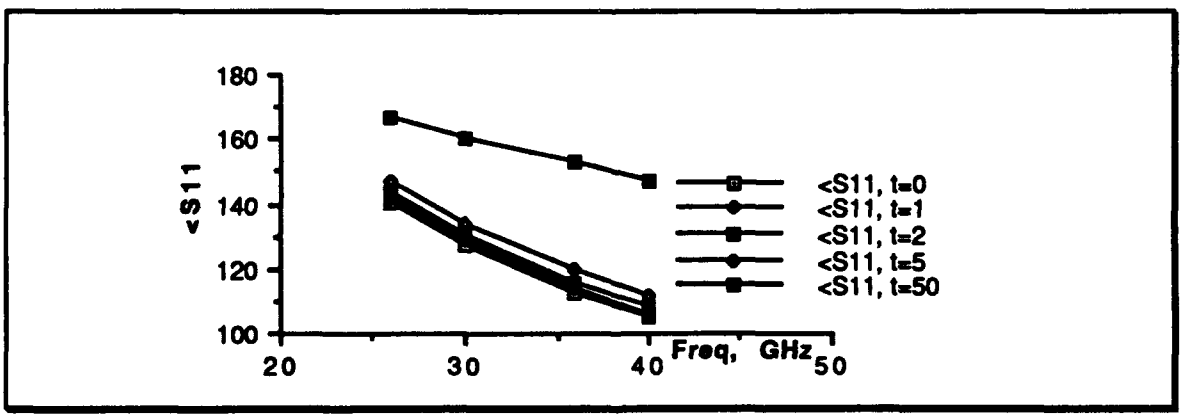


Figure 30. Angle Θ11 versus frequency for strip length T=0.5mm.

TABLE 7. S-DATA FOR STRIP LENGTH T=1MM.

	t=0 mils		t=1 mil		t=2 mils		t=5 mils		t=50 mils	
Freq	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11
26	0.933	144.74	0.941	146.17	0.945	147.13	0.954	149.52	0.995	167.19
30	0.8708	130.41	0.833	131.84	0.887	133.28	0.908	136.62	0.9875	161.94
36	0.762	111.78	0.775	113.69	0.7875	115.12	0.816	119.42	0.966	153.34
40	0.679	100.31	0.691	102.23	0.708	103.75	0.737	107.96	0.958	146.94

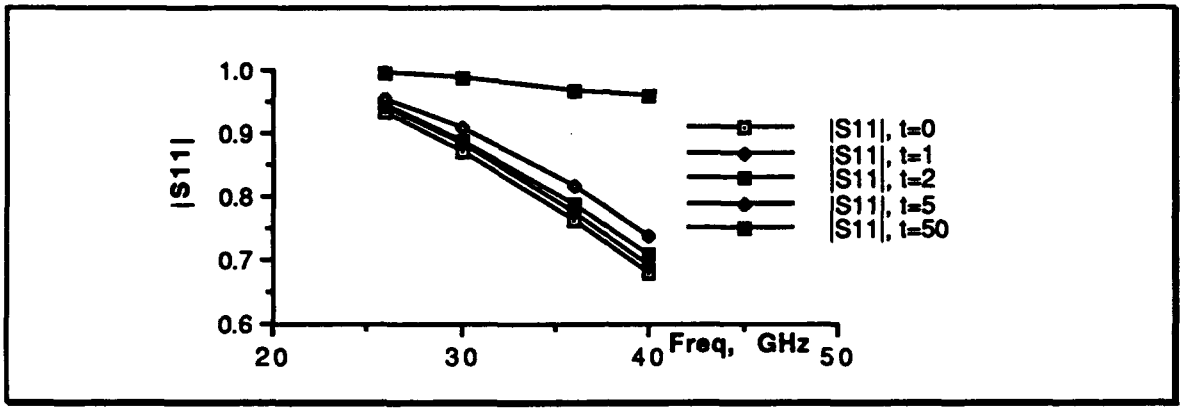


Figure 31. Magnitude S11 versus frequency for strip length T=1mm.

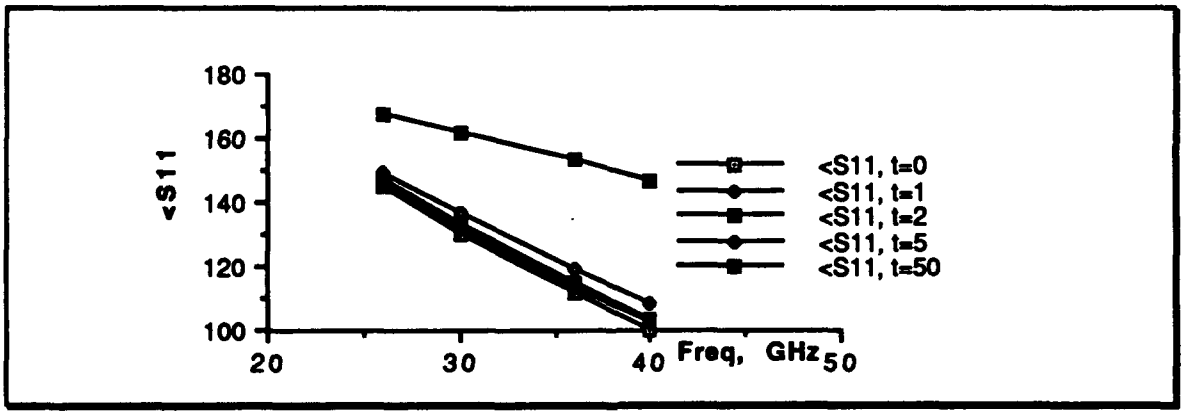


Figure 32. Angle Θ11 versus frequency for strip length T=1 mm.

TABLE 8. S-DATA FOR STRIP LENGTH T=2 MM.

	t=0 mils		t=1 mil		t=2 mils		t=5 mils		t=50 mils	
Freq	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11
26	0.983	147.61	0.987	148.56	0.989	149.04	0.991	151.43	0.996	167.86
30	0.966	132.32	0.968	134.23	0.972	135.19	0.973	138.15	0.986	162.13
36	0.904	109.87	0.912	111.78	0.916	113.69	0.920	117.99	0.976	153.82
40	0.833	94.108	0.841	95.06	0.85	97.45	0.851	102.70	0.966	146.65

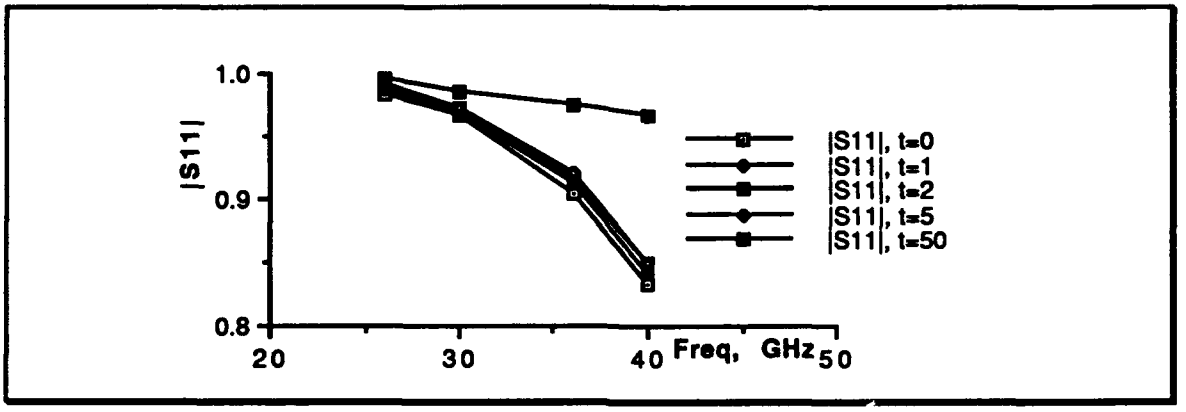


Figure 33. Magnitude of S11 versus frequency for strip length T=2 mm.

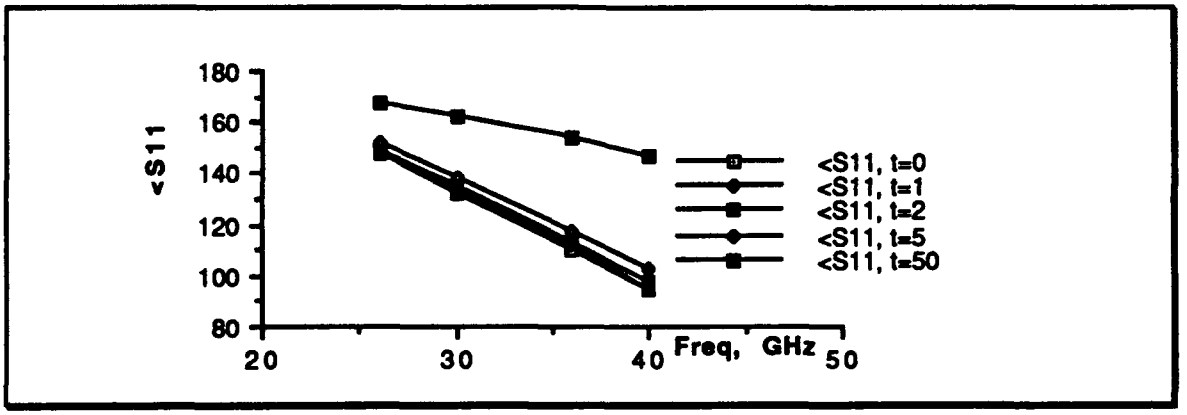


Figure 34. Angle Θ11 versus frequency for strip length T=2 mm.

TABLE 9. S-DATA FOR STRIP LENGTH T=5 MM.

	t=0 mils		t=1 mil		t=2 mils		t=5 mils		t=50 mils	
Freq	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11	|S11|	Θ11
26	0.995	148.08	0.996	149.04	0.997	150.00	0.998	152.38	0.999	167.96
30	0.985	132.80	0.986	134.71	0.987	135.66	0.988	138.50	0.997	162.42
36	0.975	108.91	0.976	110.82	0.977	112.70	0.978	117.5	0.995	153.82
40	0.965	85.98	0.966	88.85	0.967	91.7	0.968	97.45	0.993	146.03

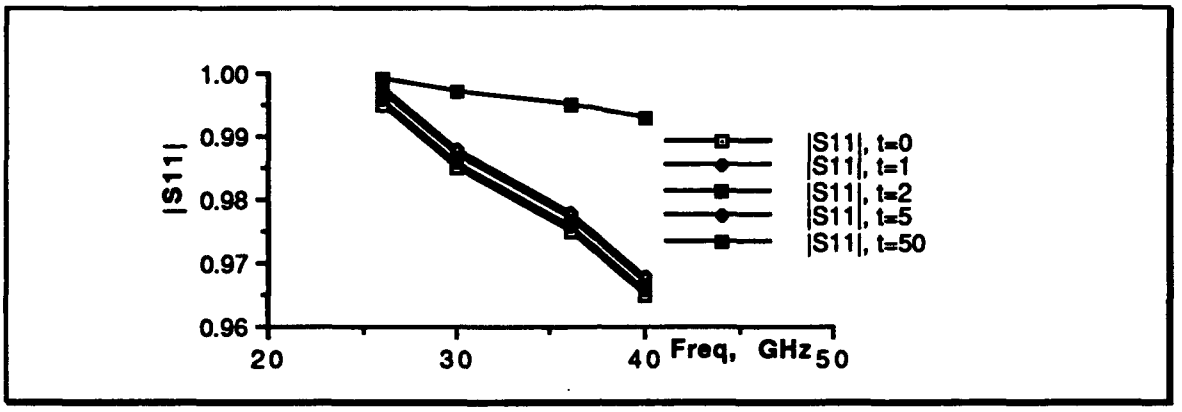


Figure 35. Magnitude for S11 versus frequency for strip length T=5 mm.

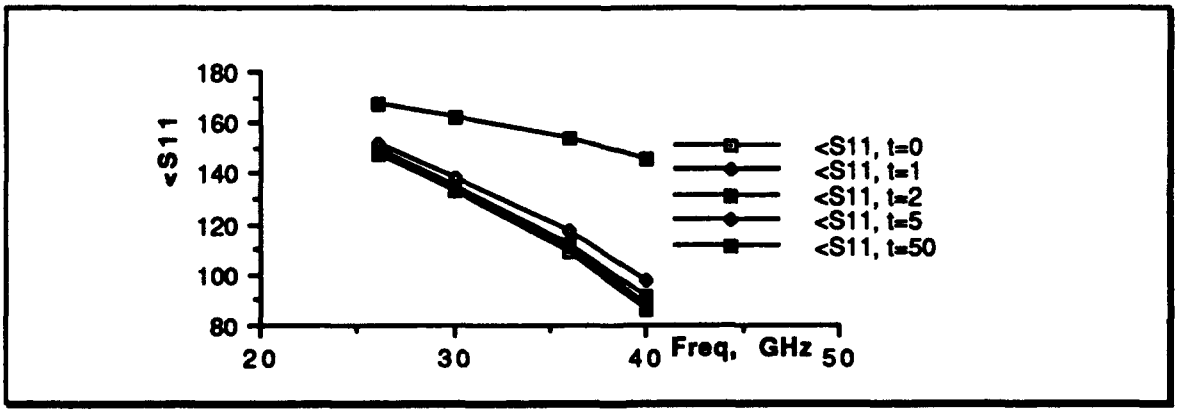


Figure 36. Angle Θ11 versus frequency for strip length T=5 mm.

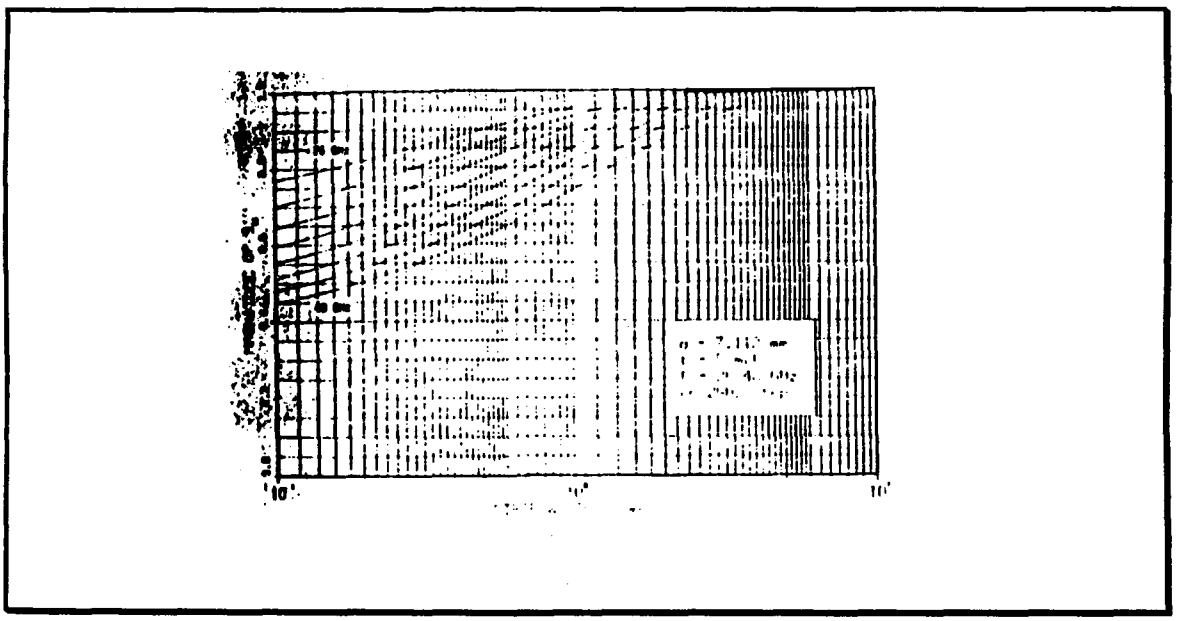


Figure 37. Magnitude of S11 for strip with thickness t=5 mils [Ref 10].

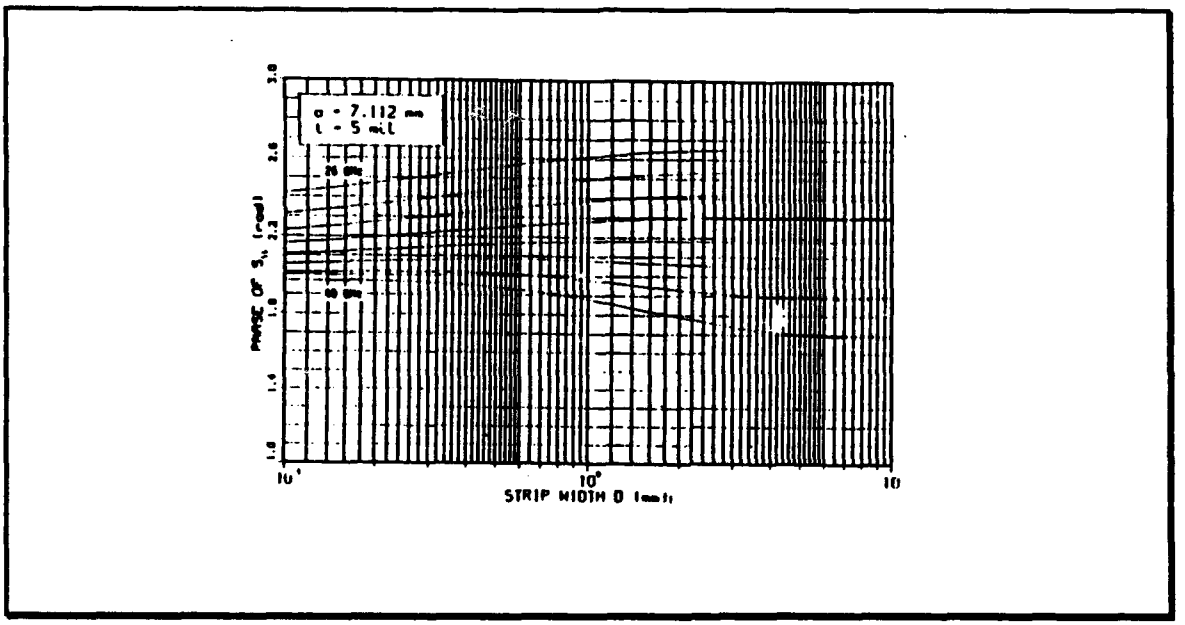


Figure 38. Angle of the S11 for strip with thickness t=5 mils [Ref 10].

APPENDIX. B. MAGNITUDE, ANGLE, SMITH CHART PLOT OF MODEL AND DATA

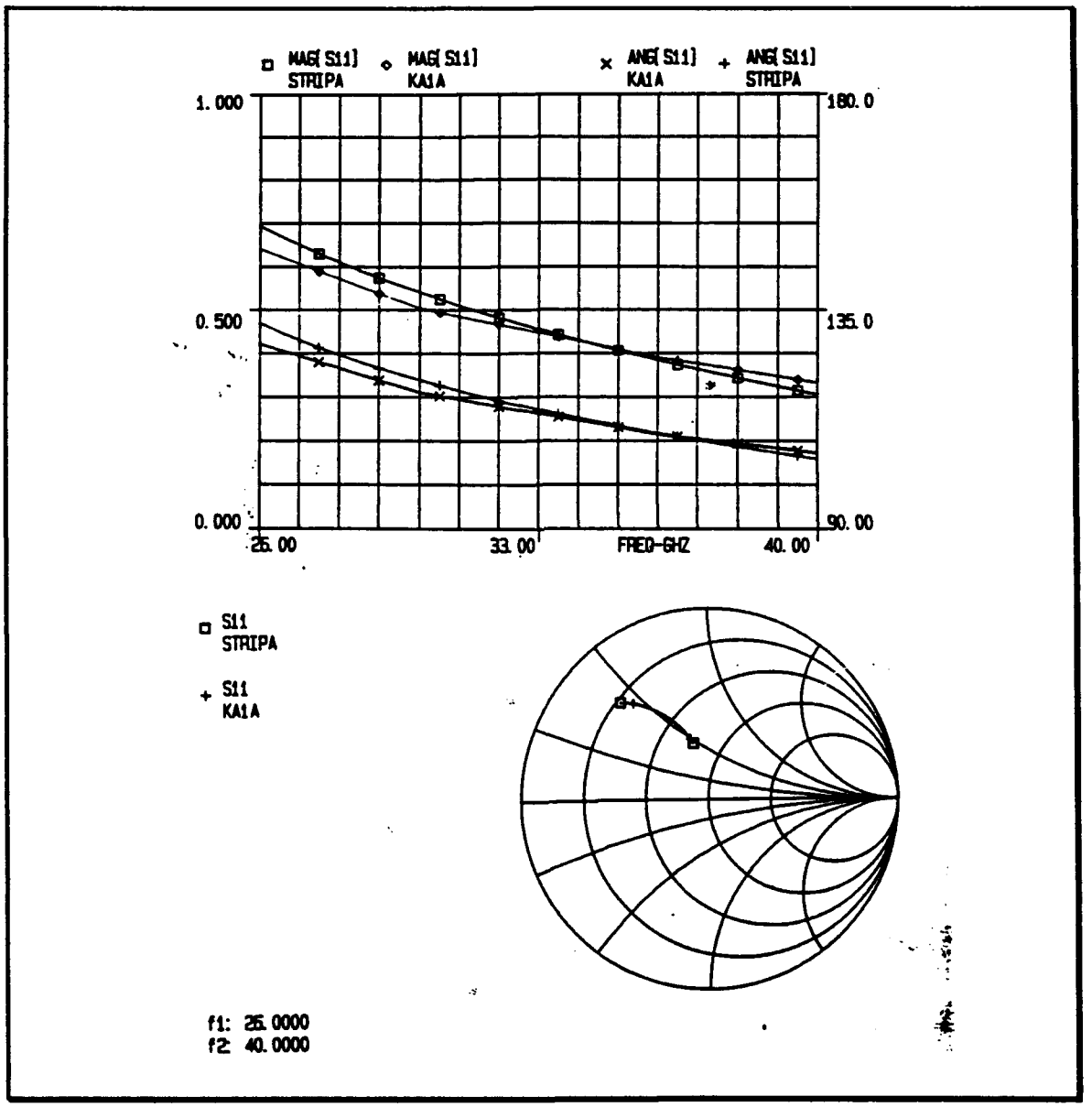


Figure 39. Plots for WR(28), w/b=1, T=0.1 mm, t=0 mils.

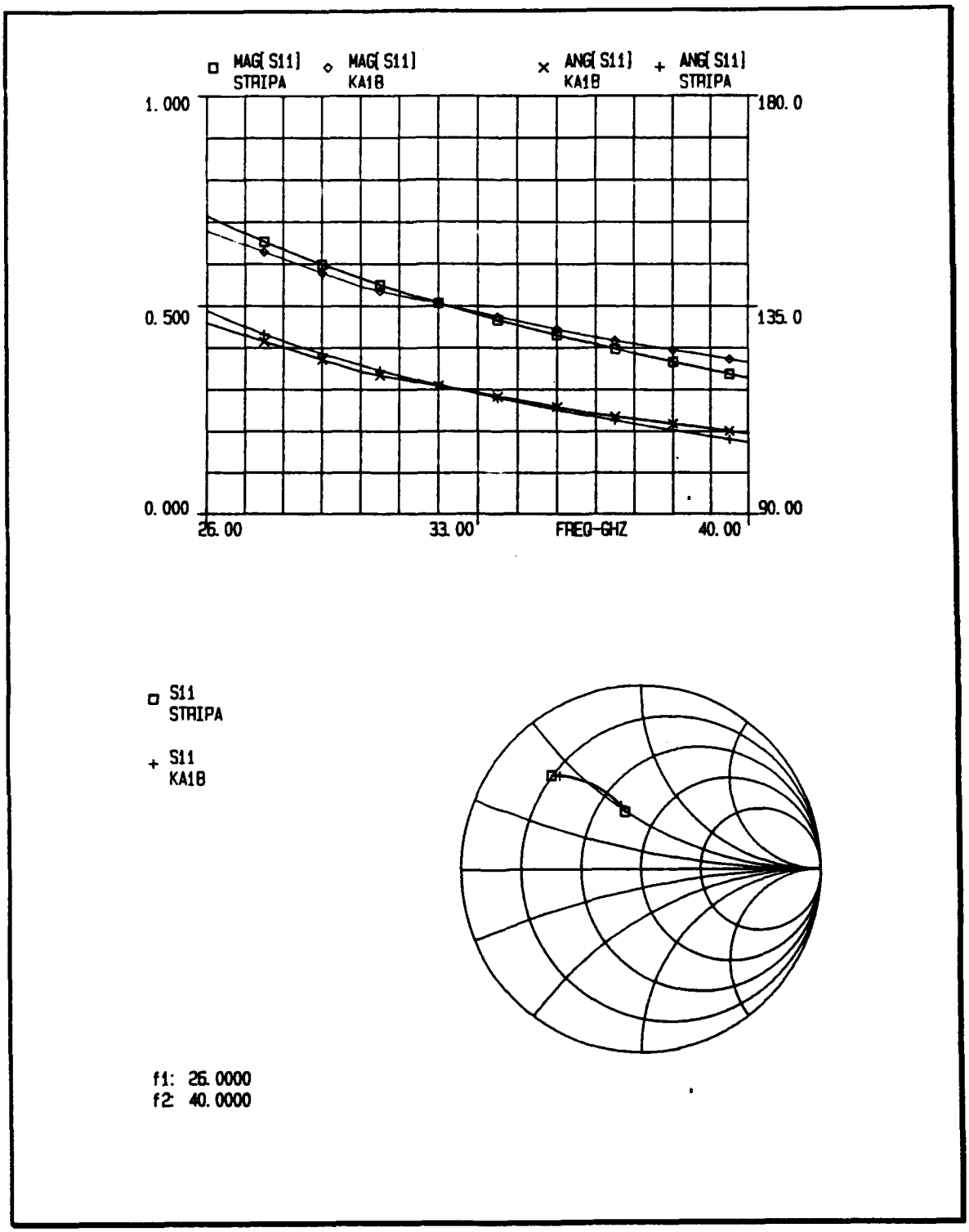


Figure 40. Plots for WR(28), w/b=1, T=0.1 mm, t=1 mils.

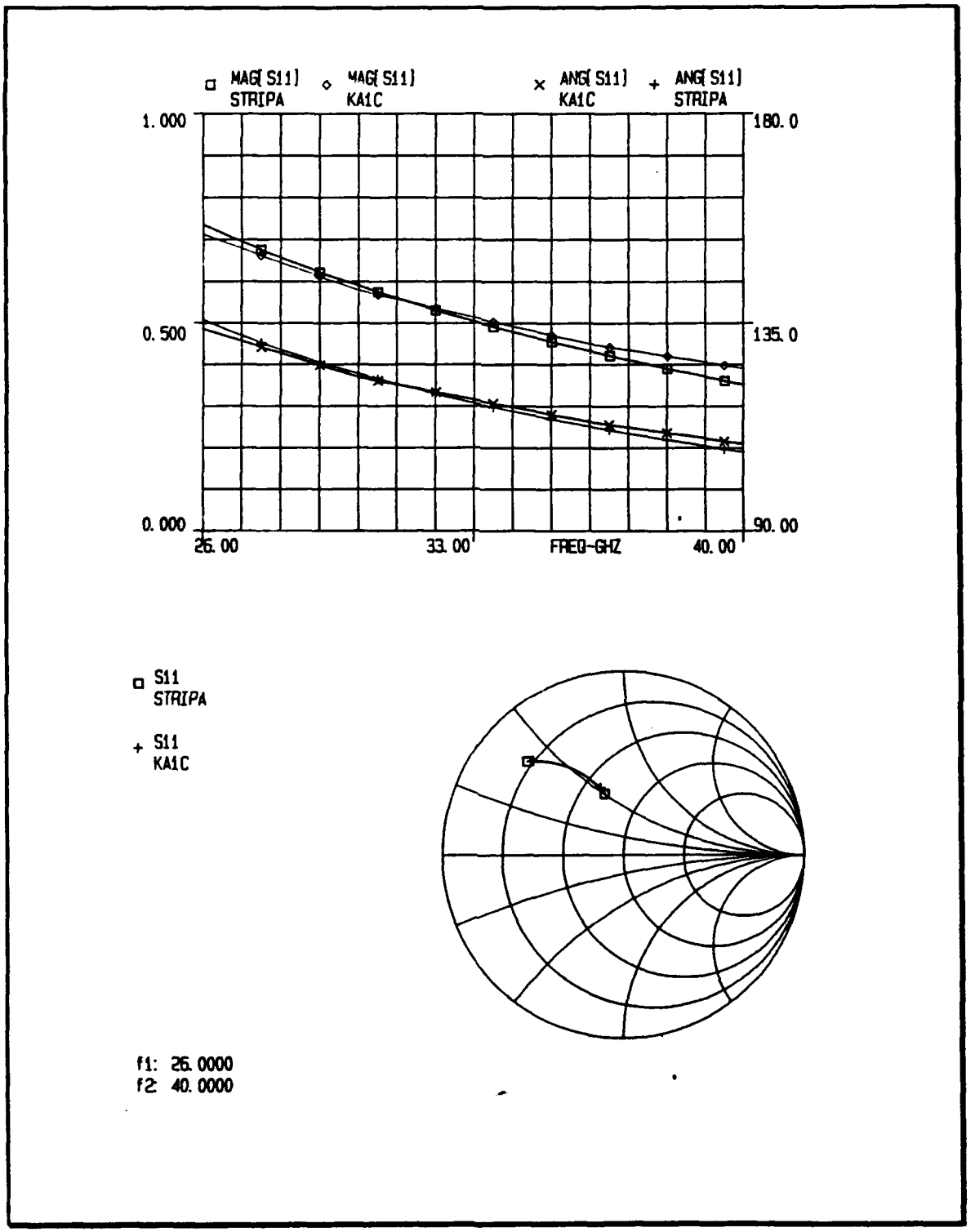


Figure 41. Plots for WR(28), w/b=1, T=0.1 mm, t=2 mils.

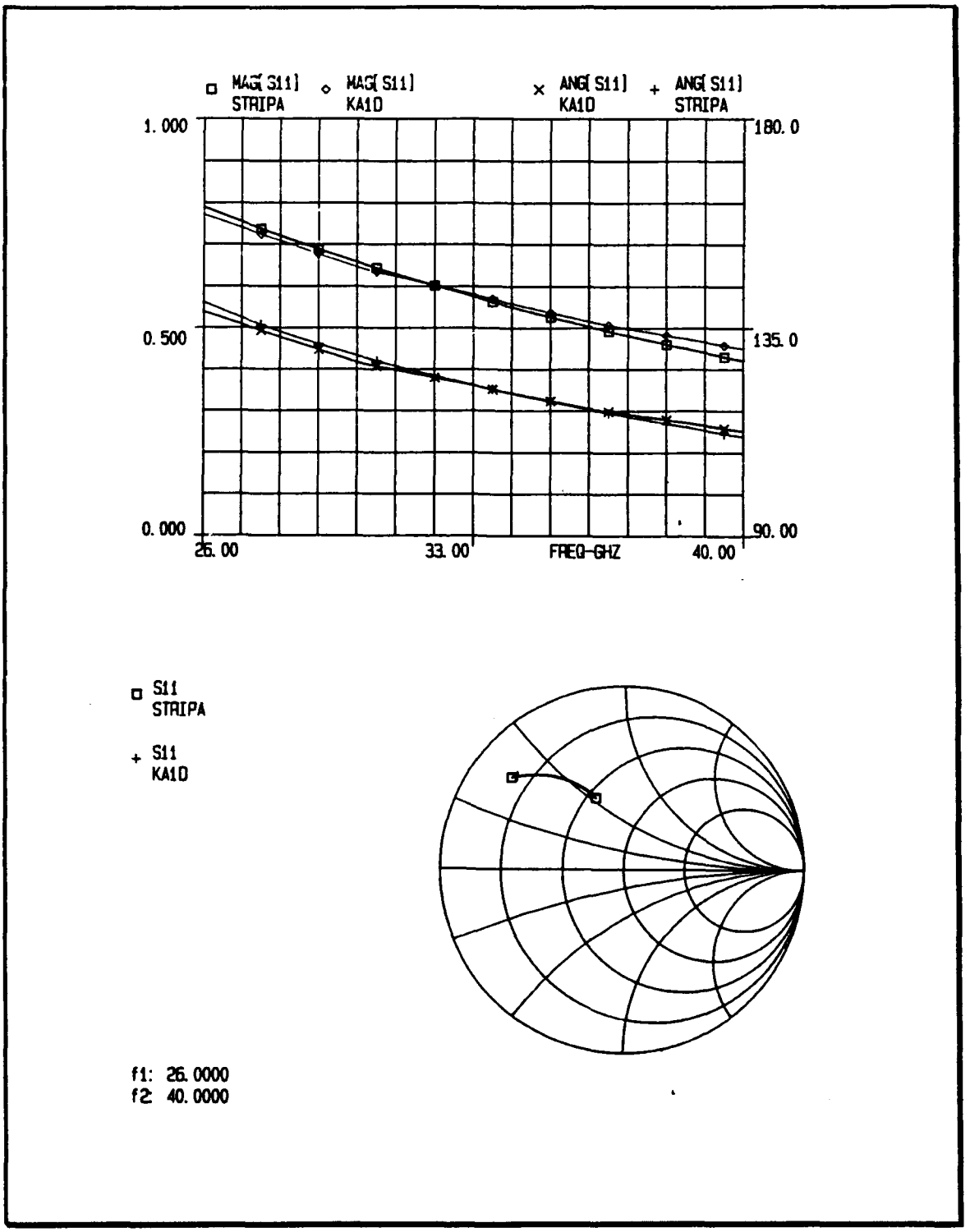


Figure 42. Plots for WR(28),w/b=1, T=0.1 mm, t=5 mils.

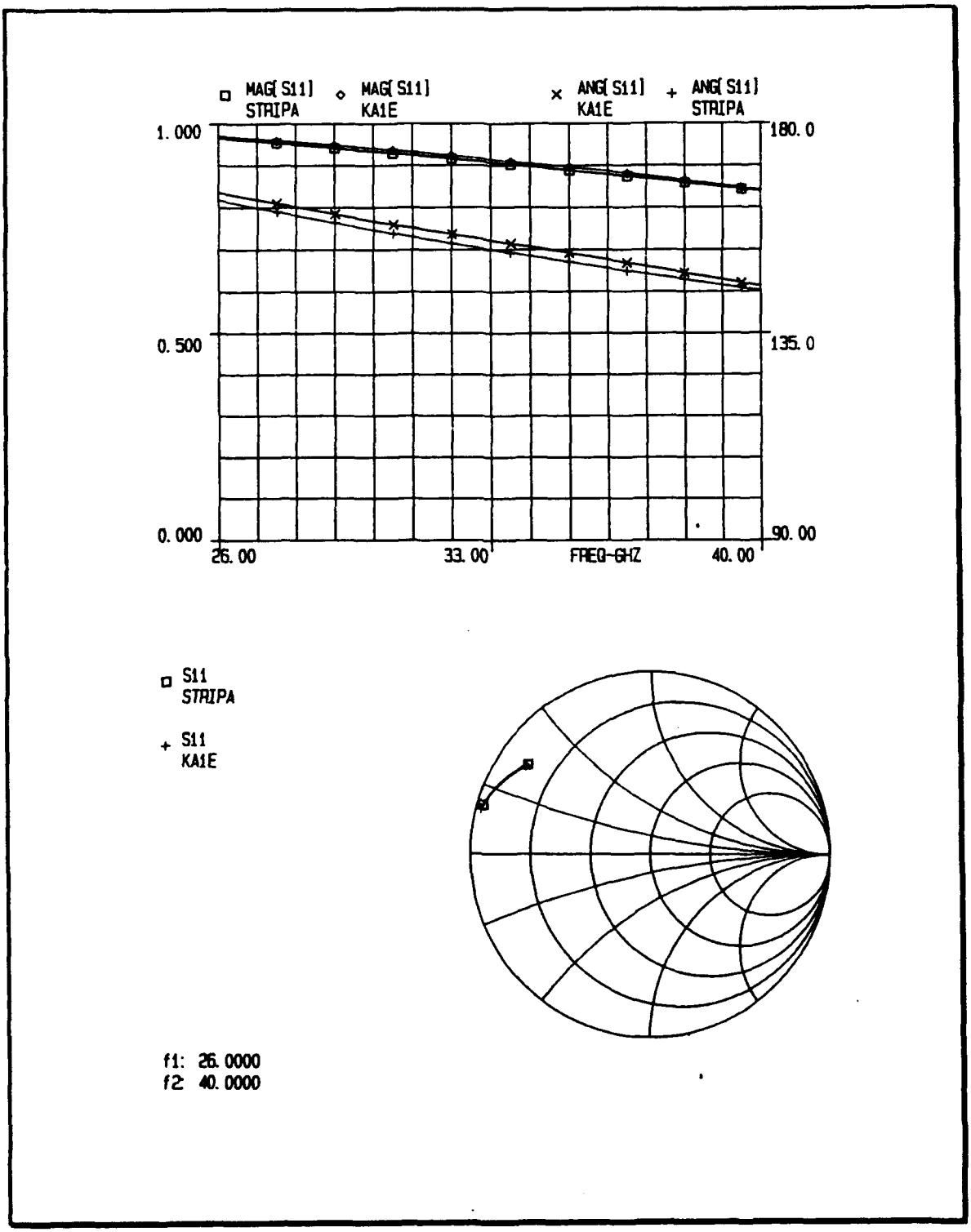
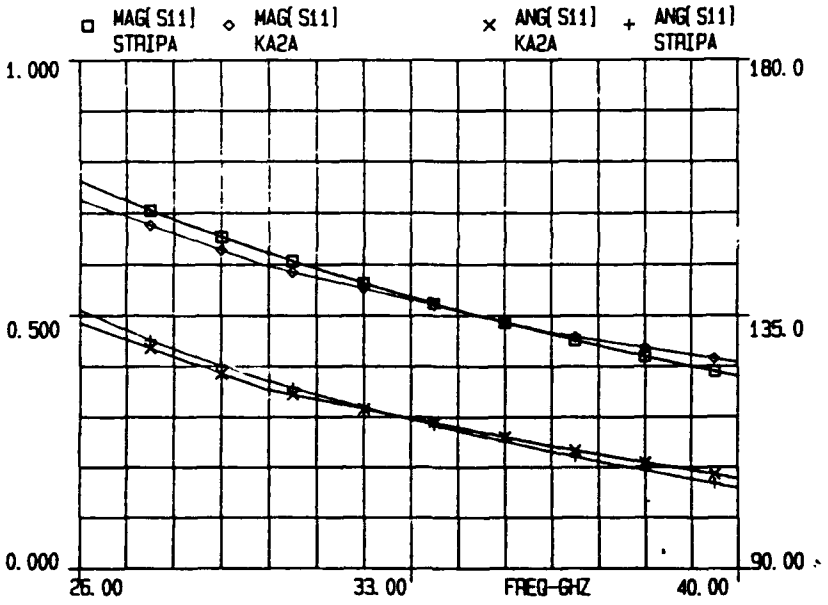
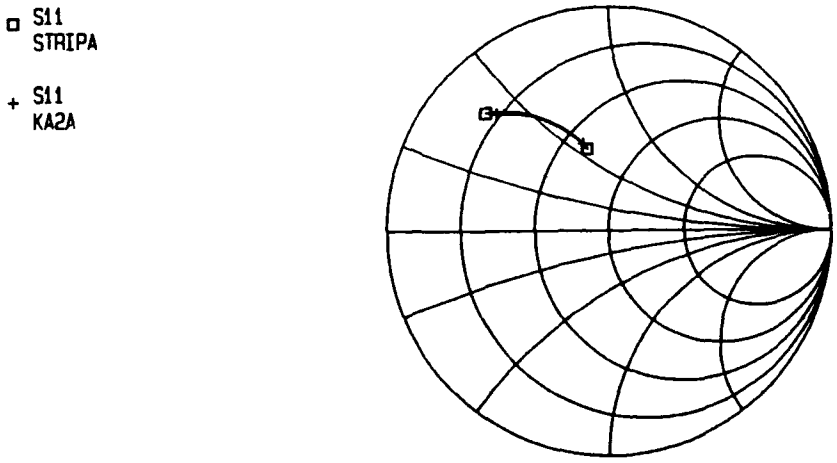


Figure 43. Plots for WR(28), w/b=1, T=0.1 mm, t=50 mils.





f1: 26.0000
f2: 40.0000

Figure 44. Plots for WR(28), w/b=1, T=0.2 mm, t=0 mils.

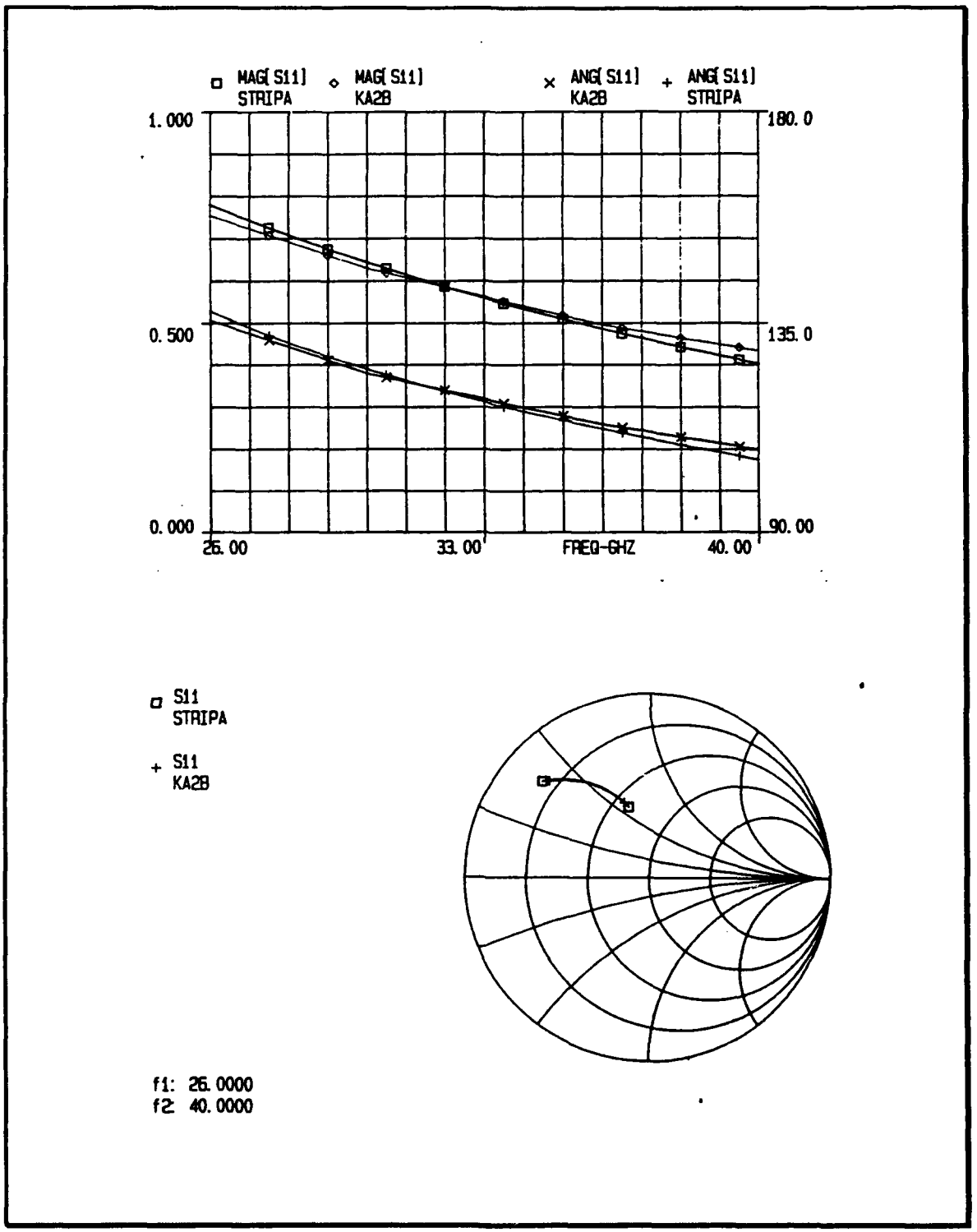


Figure 45. Plots for WR(28), w/b=1, T=0.2 mm, t=1 mils.

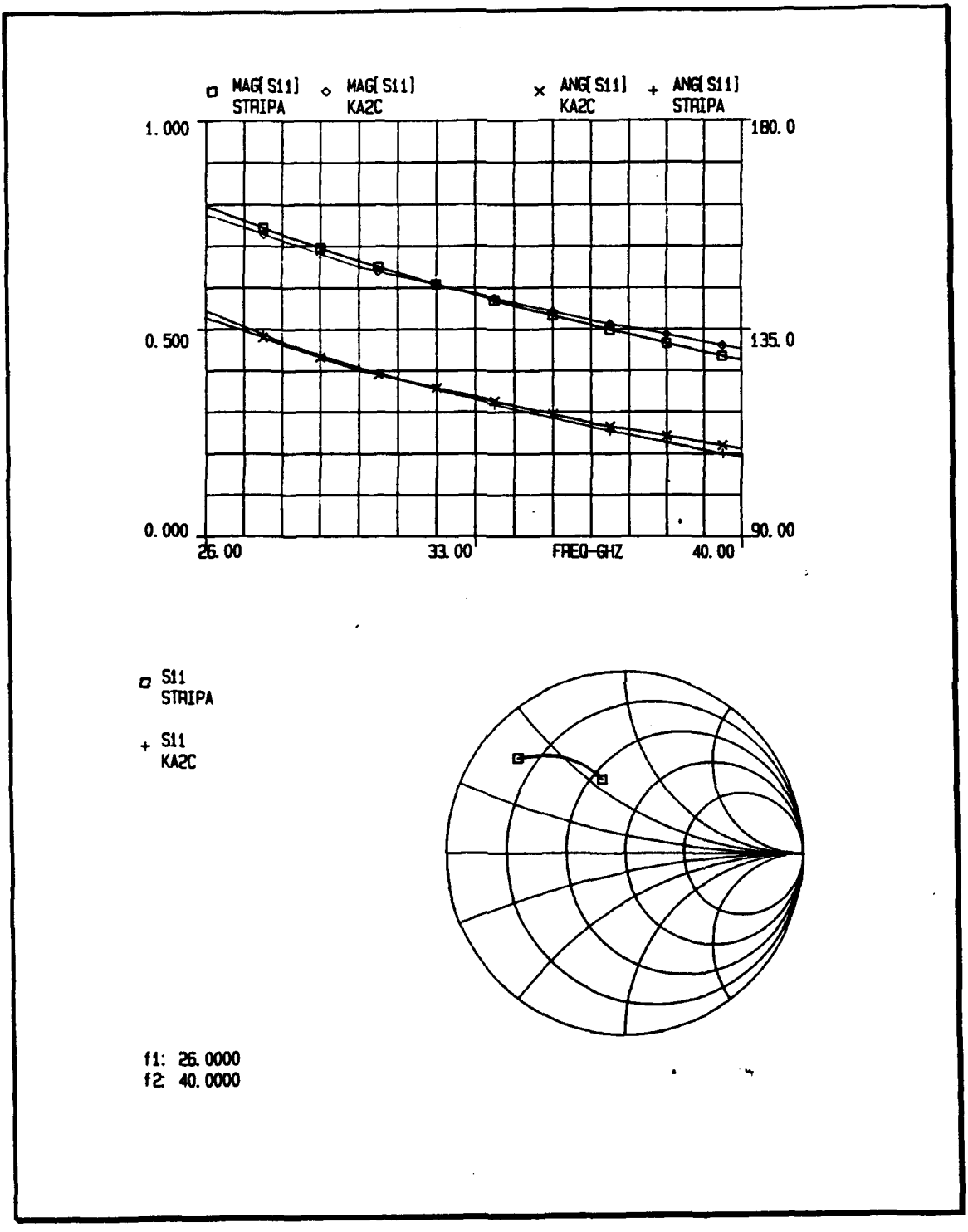


Figure 46. Plots for WR(28), w/b=1, T=0.2 mm, t=2 mils.

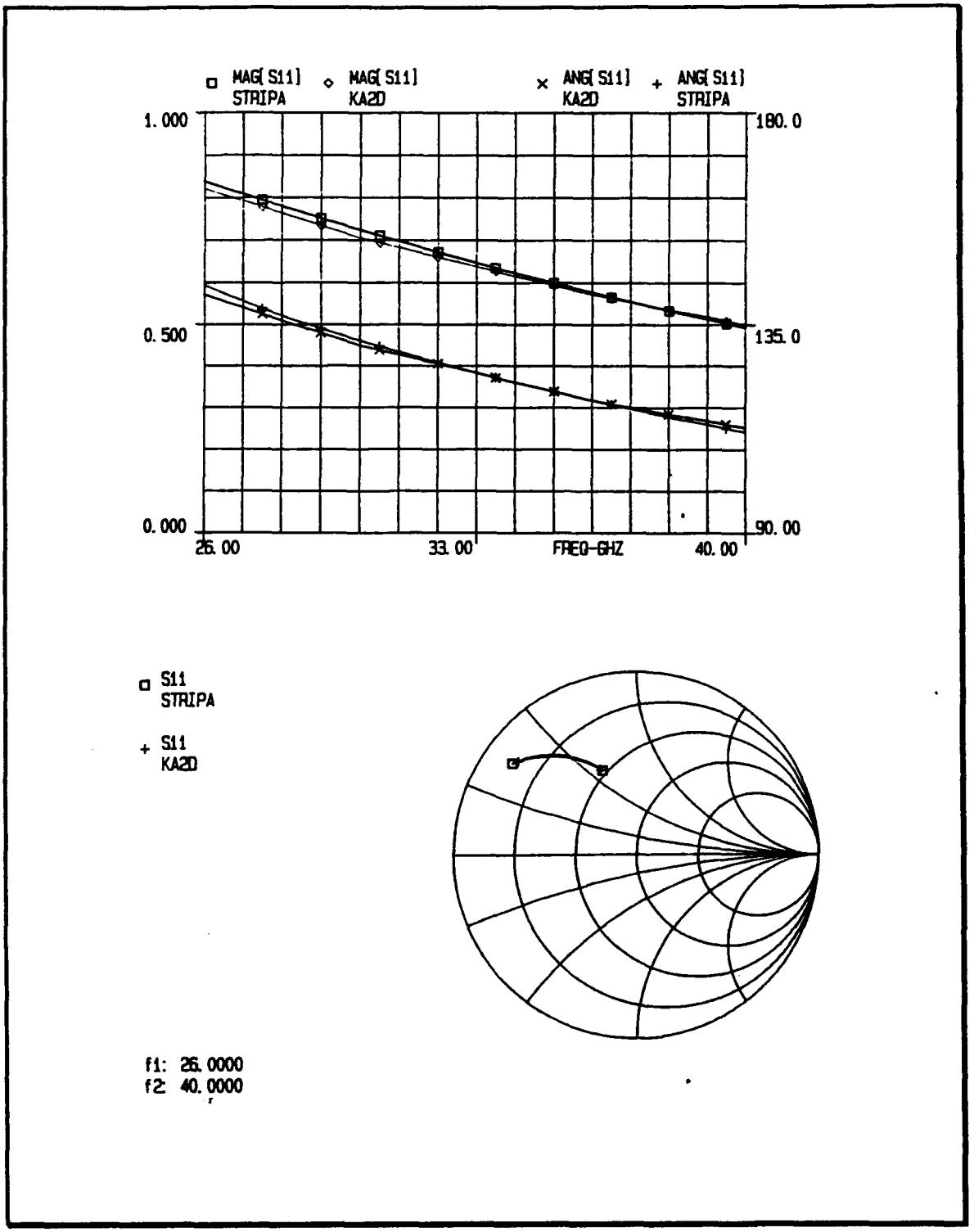


Figure 47. Plots for WR(28), w/b=1, T=0,2 mm, t=5 mils.

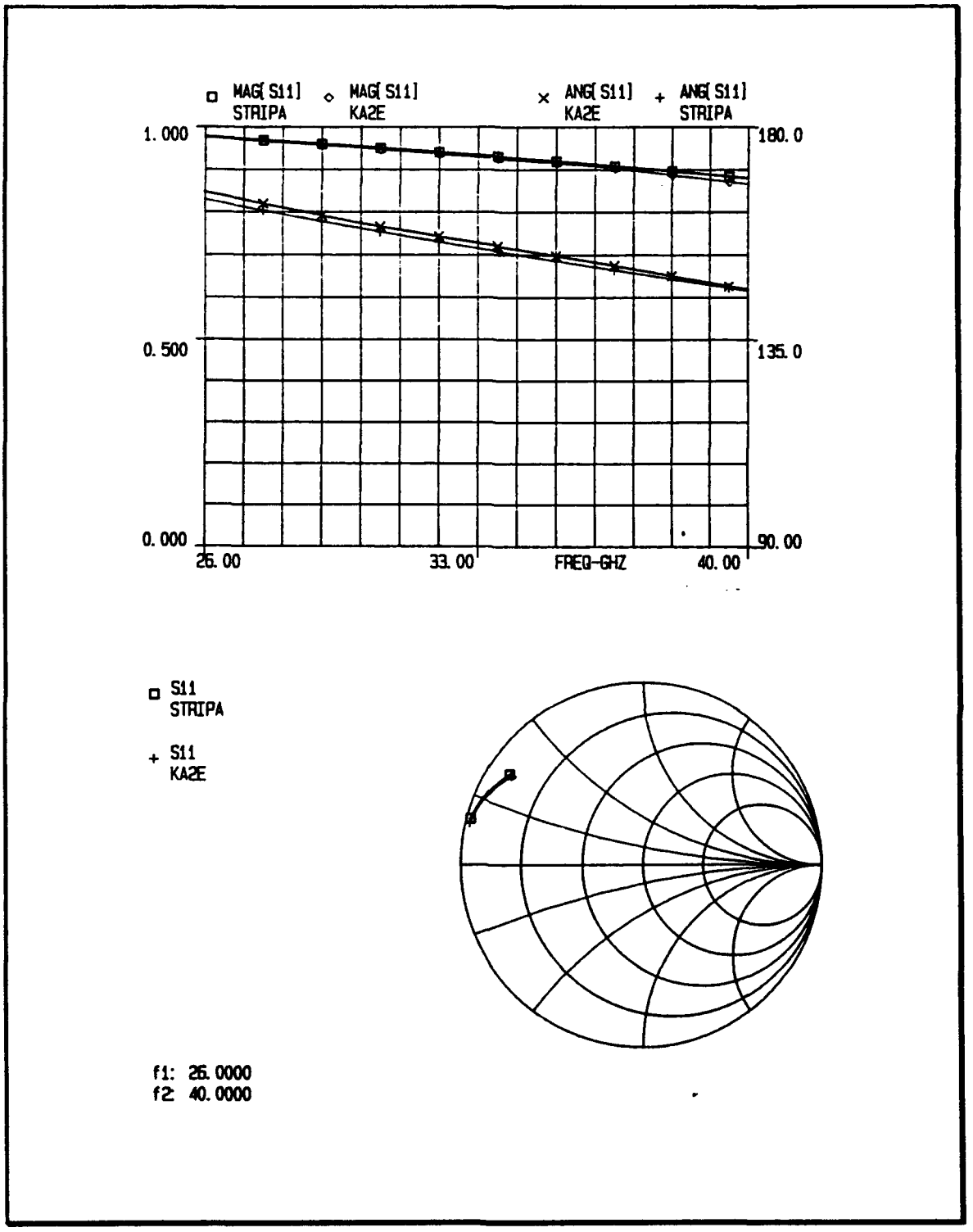


Figure 48. Plots for WR(28), T=0.2 mm, t=50 mils.

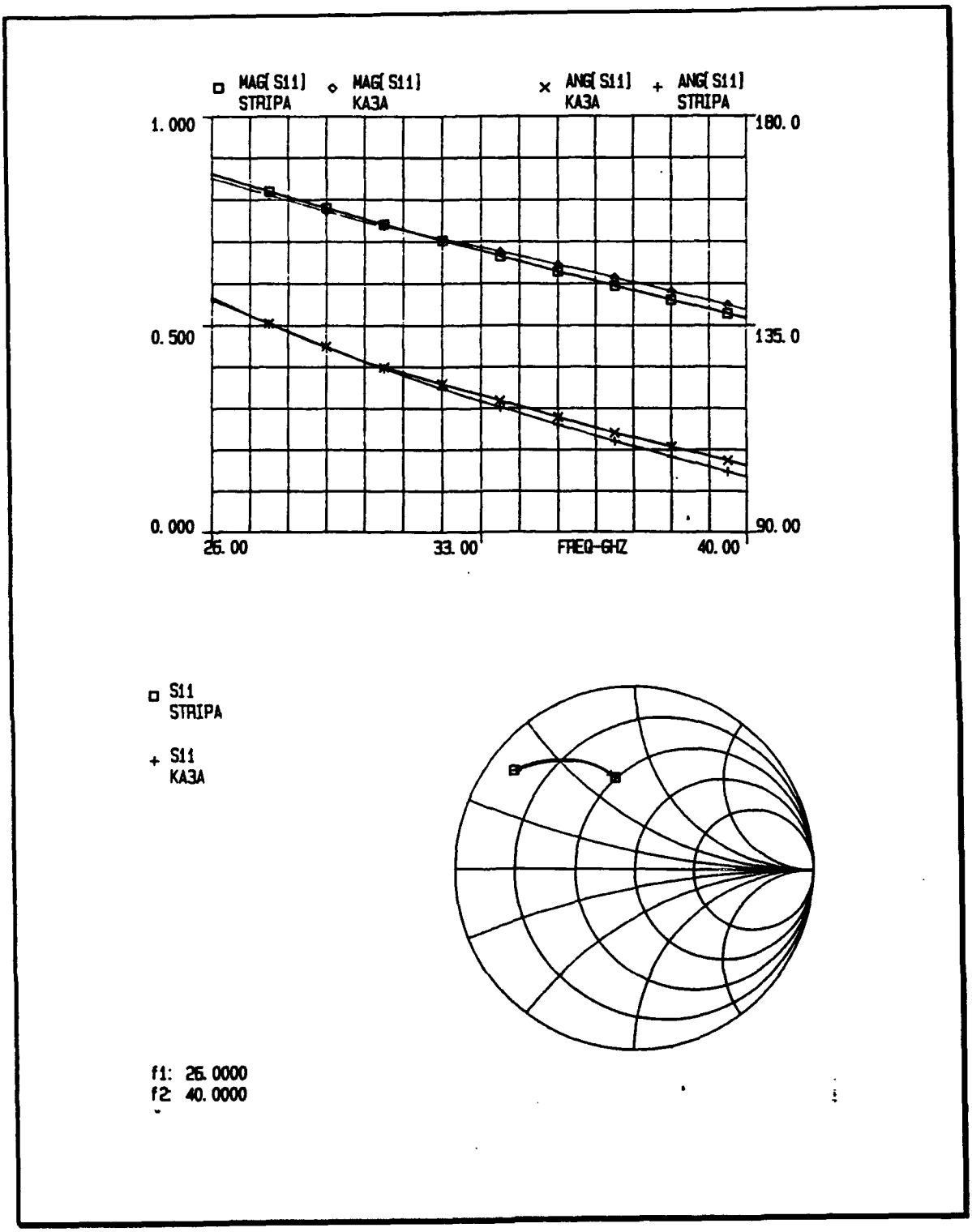


Figure 49. Plots for WR(28), w/b=1,T=0.5 mm, t=0 mils.

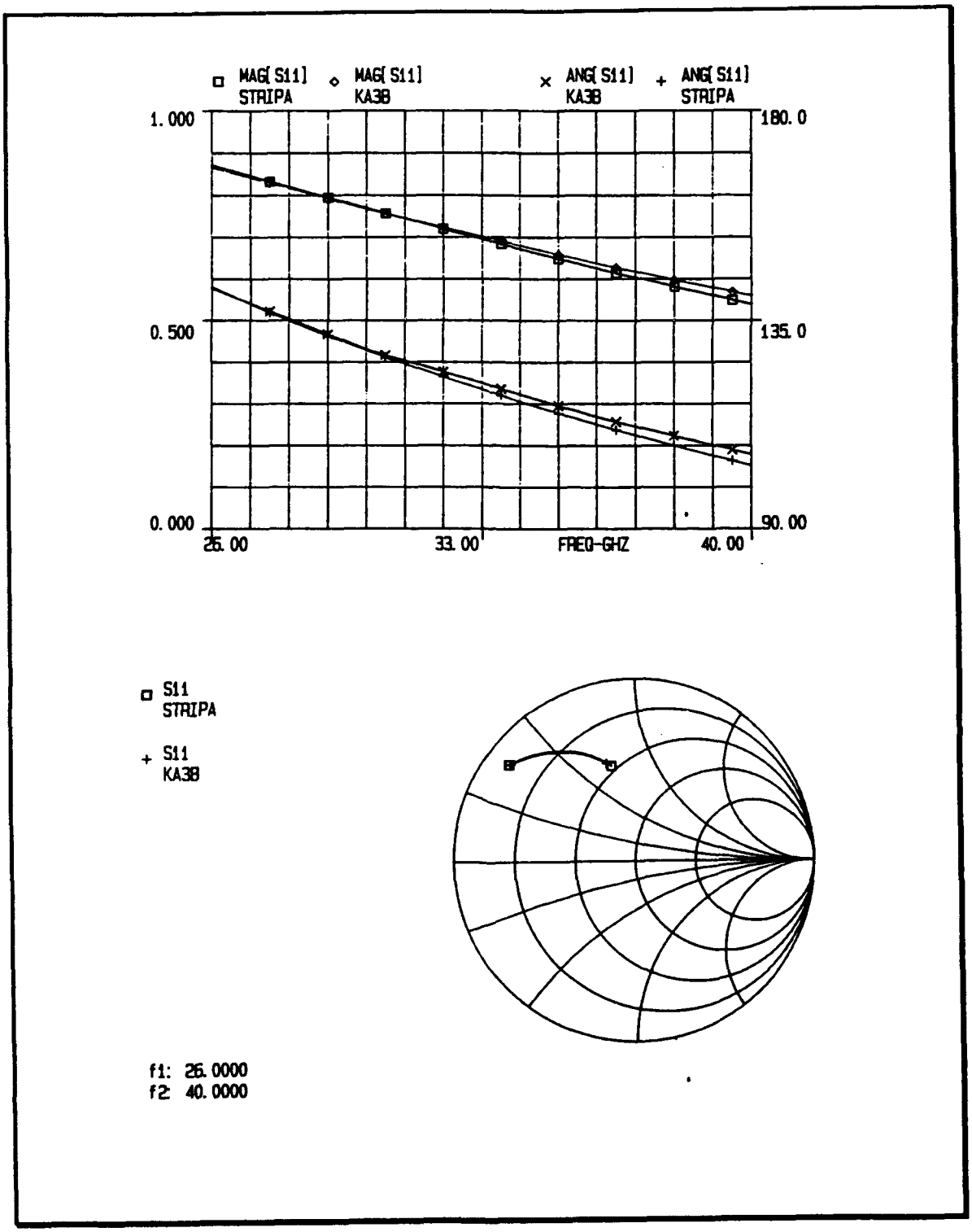


Figure 50. Plots for WR(28), w/b=1, T=0.5 mm, t=1 mils.

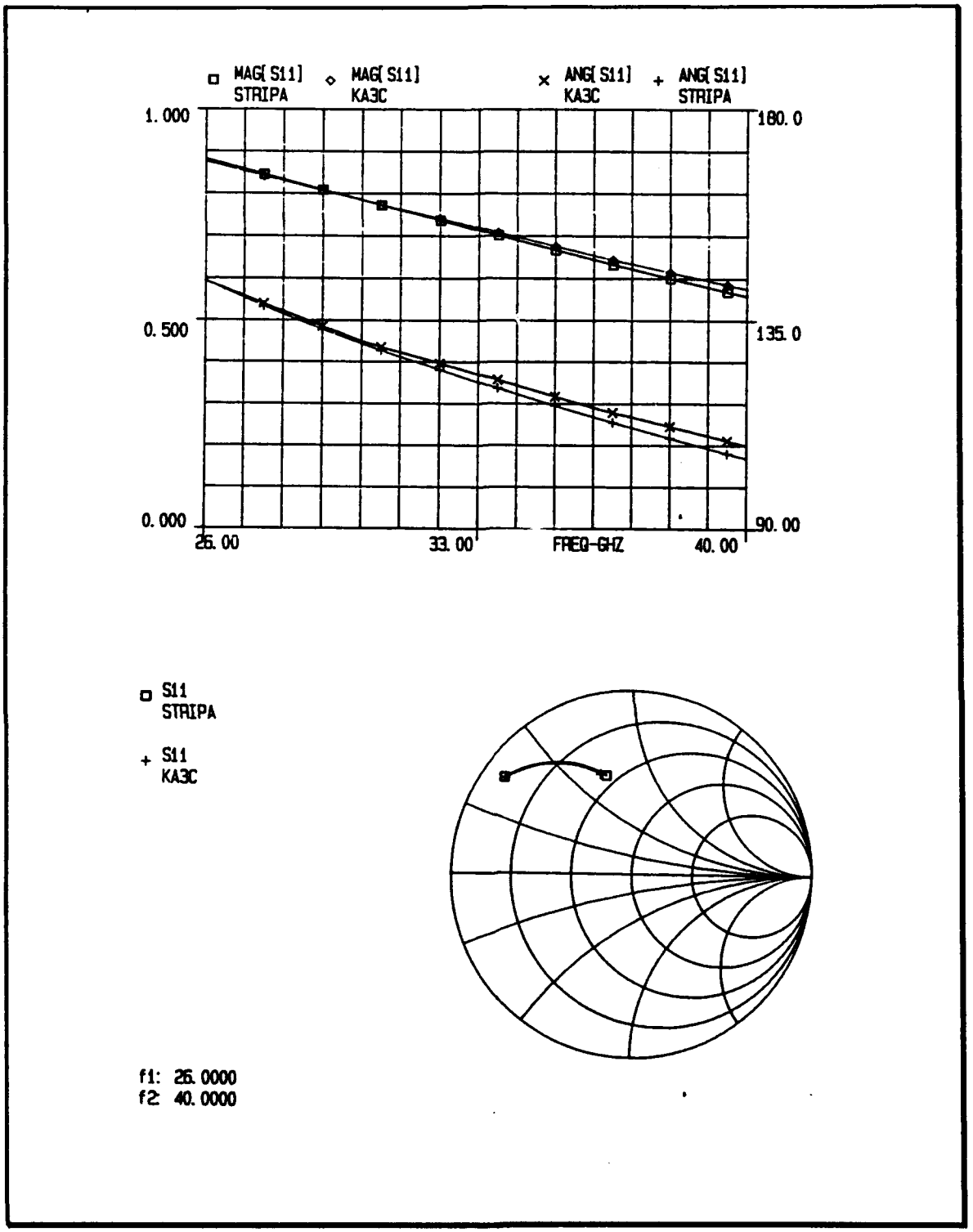


Figure 51. Plots for WR(28), w/b=1, T=0.5 mm, t=2 mils.

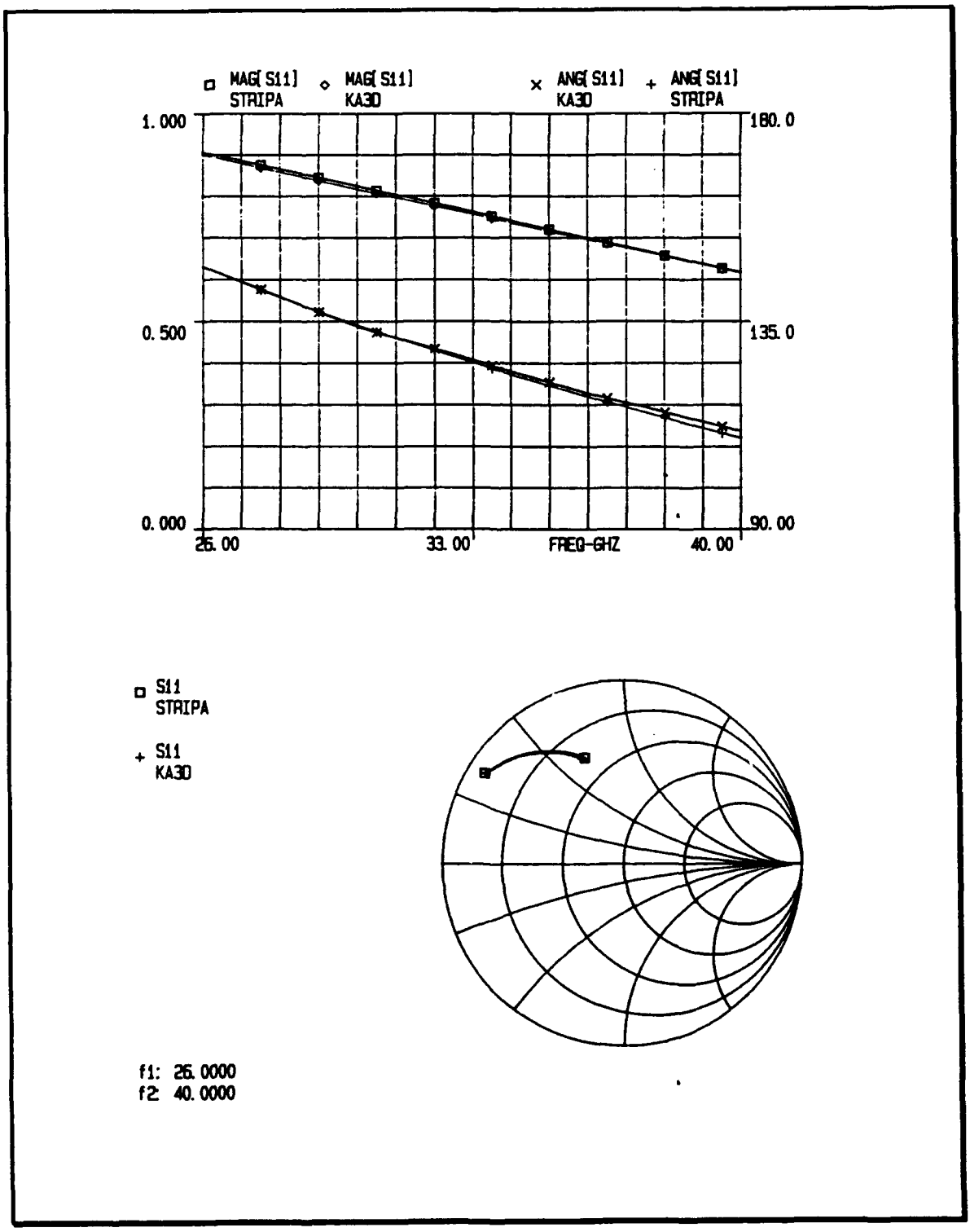


Figure 52. Plots for WR(28), w/b=1, T=0.5 mm, t=5 mils.

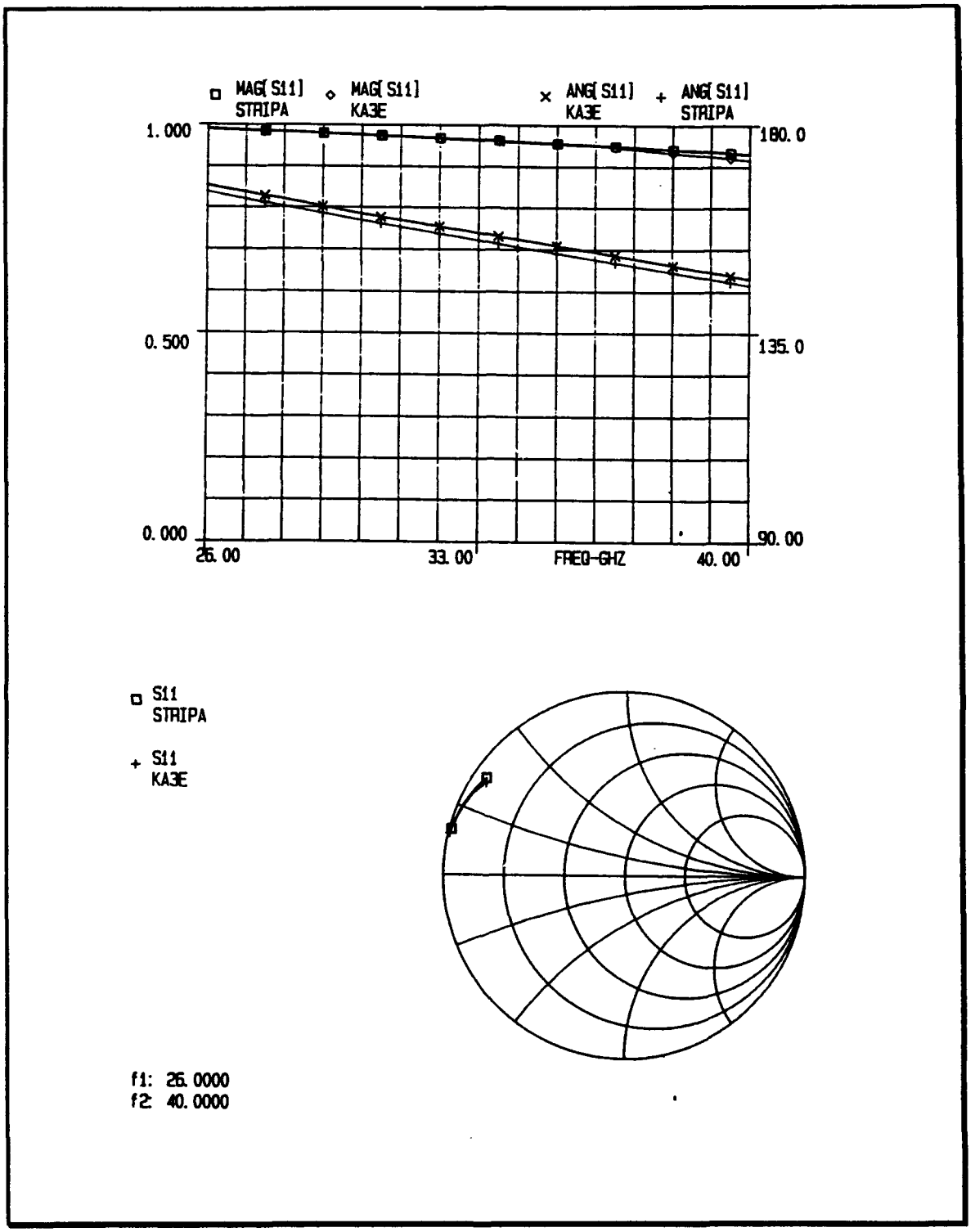


Figure 53. Plots for WR(28), w/b=1, T=0.5, t=50 mils.

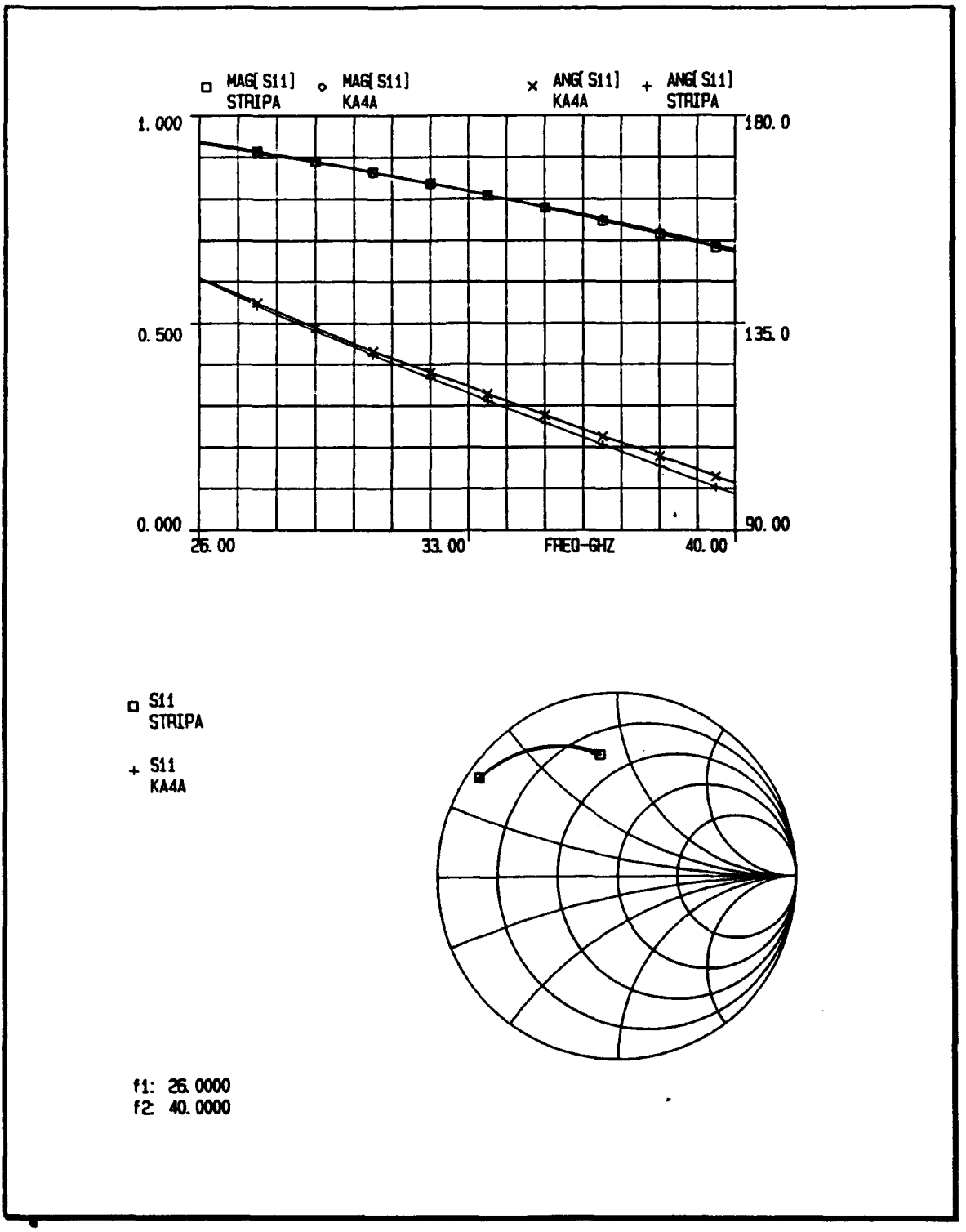


Figure 54. Plots for WR(28), w/b=1, T=1 mm, t=0 mils.

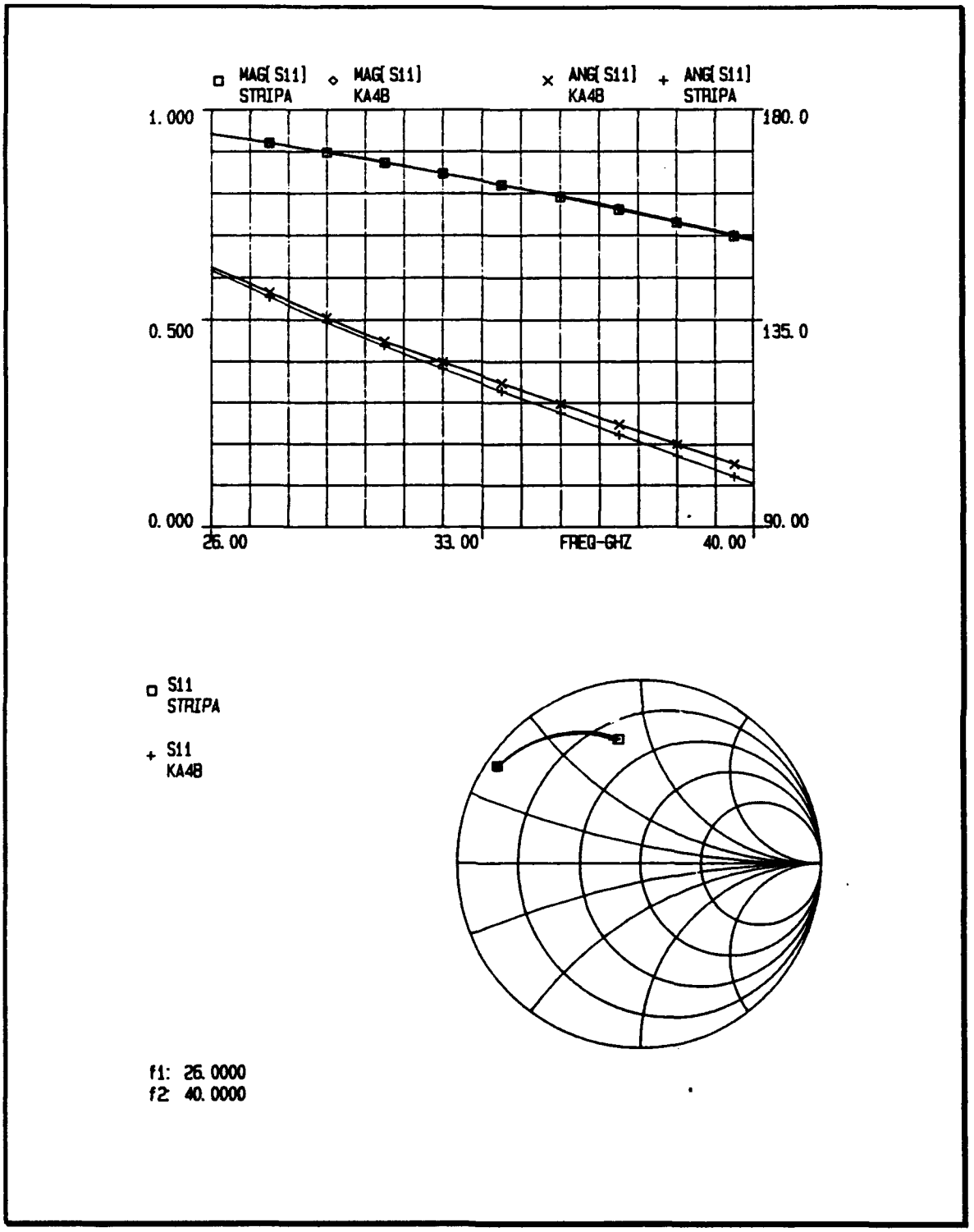


Figure 55. Plots for WR(28), w/b=1, T=1 mm, t=1 mils.

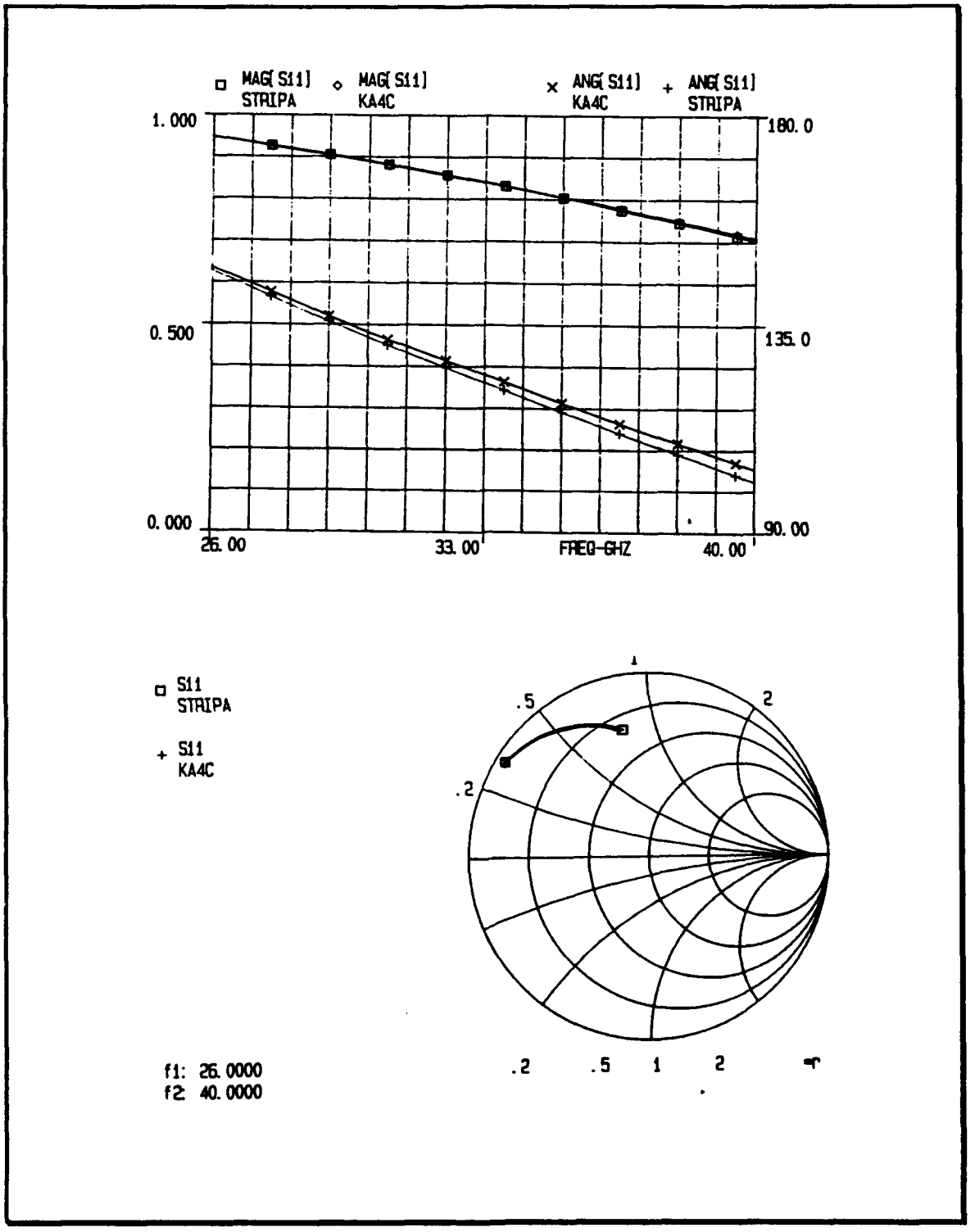


Figure 56. Plots for WR(28), w/b=1, T=1 mm, t=2 mils.

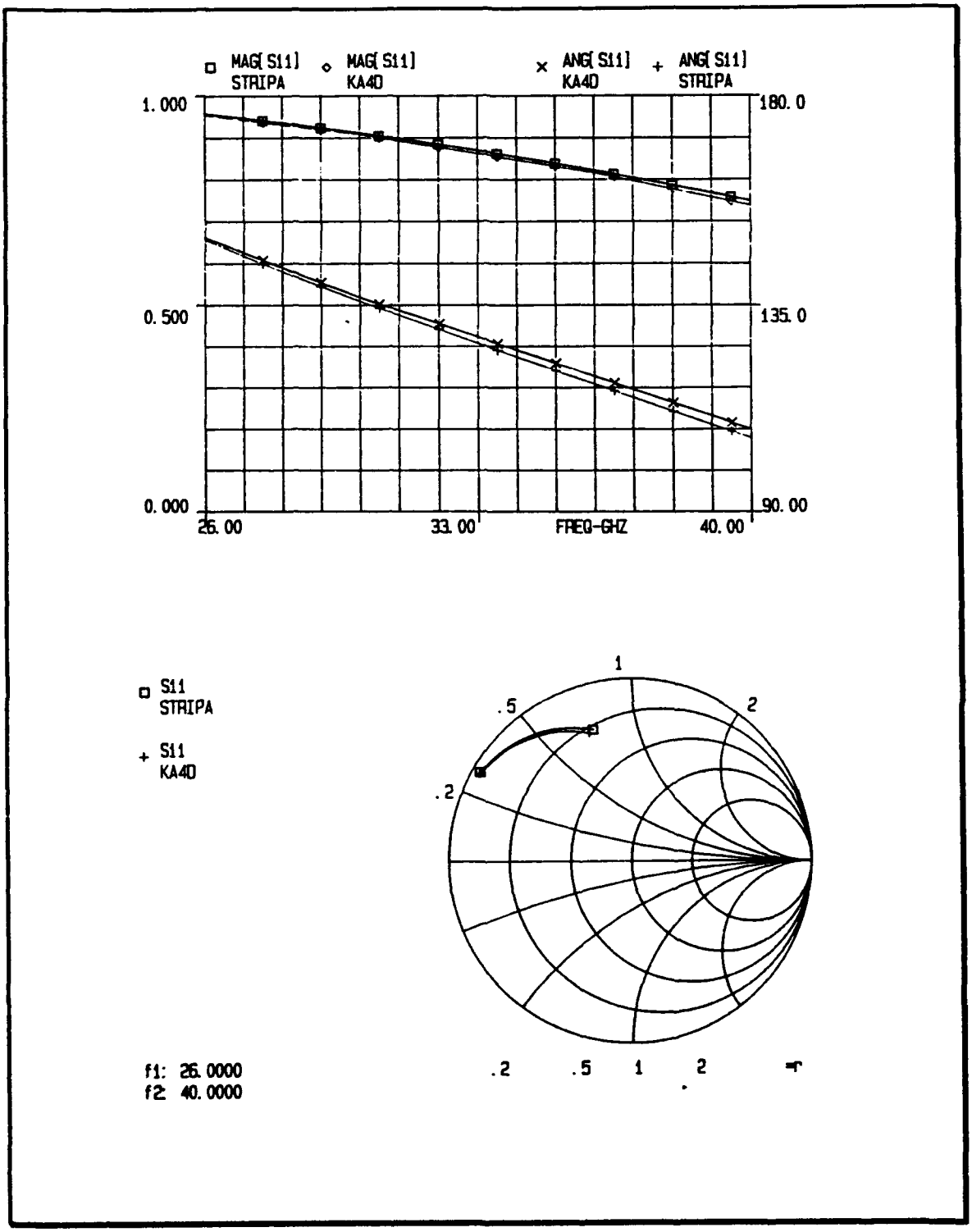


Figure 57. Plots for WR(28), w/b=1, T=1mm, t=5 mils.

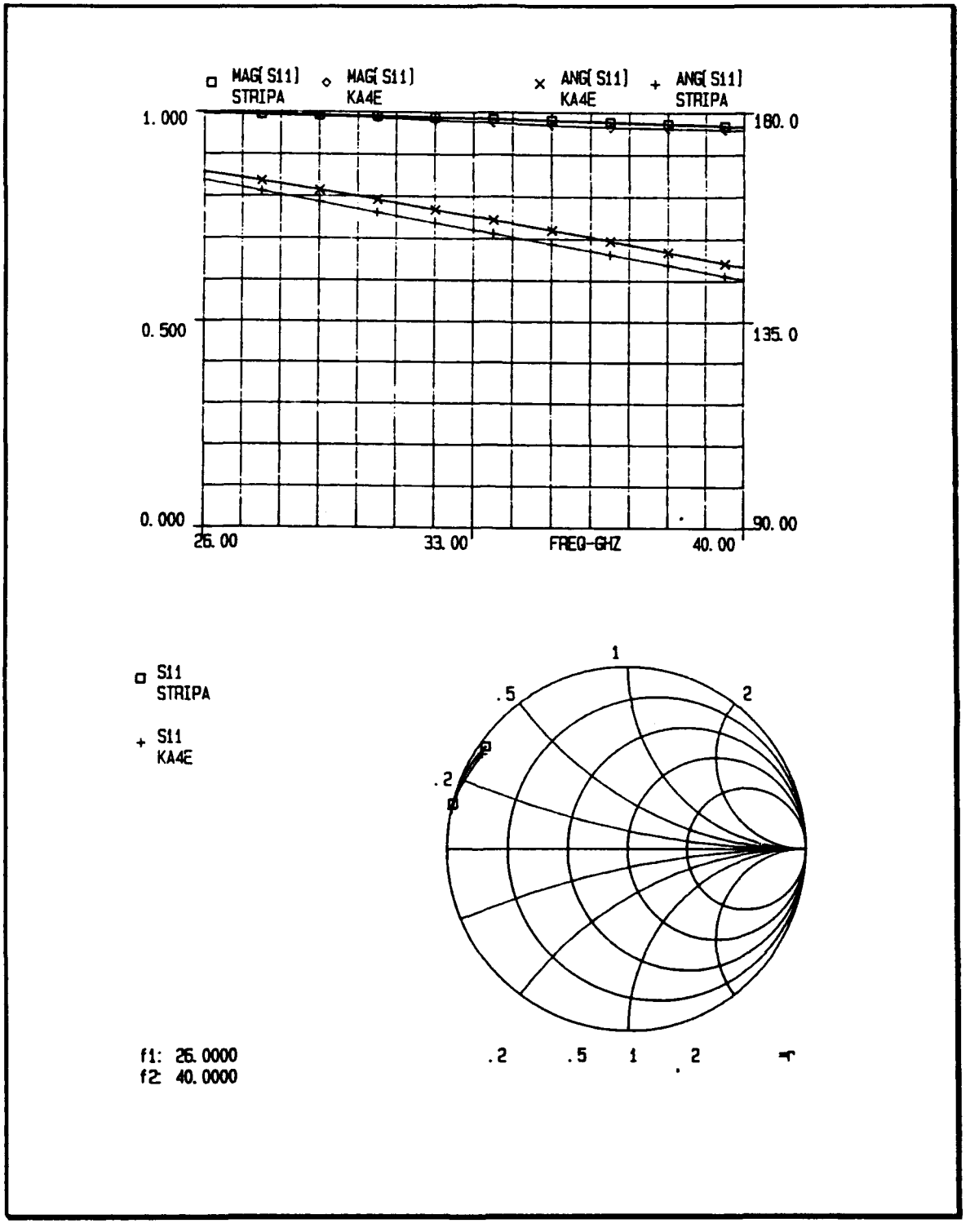


Figure 58. Plots for WR(28), w/b=1, T=1 mm, t=50 mils.

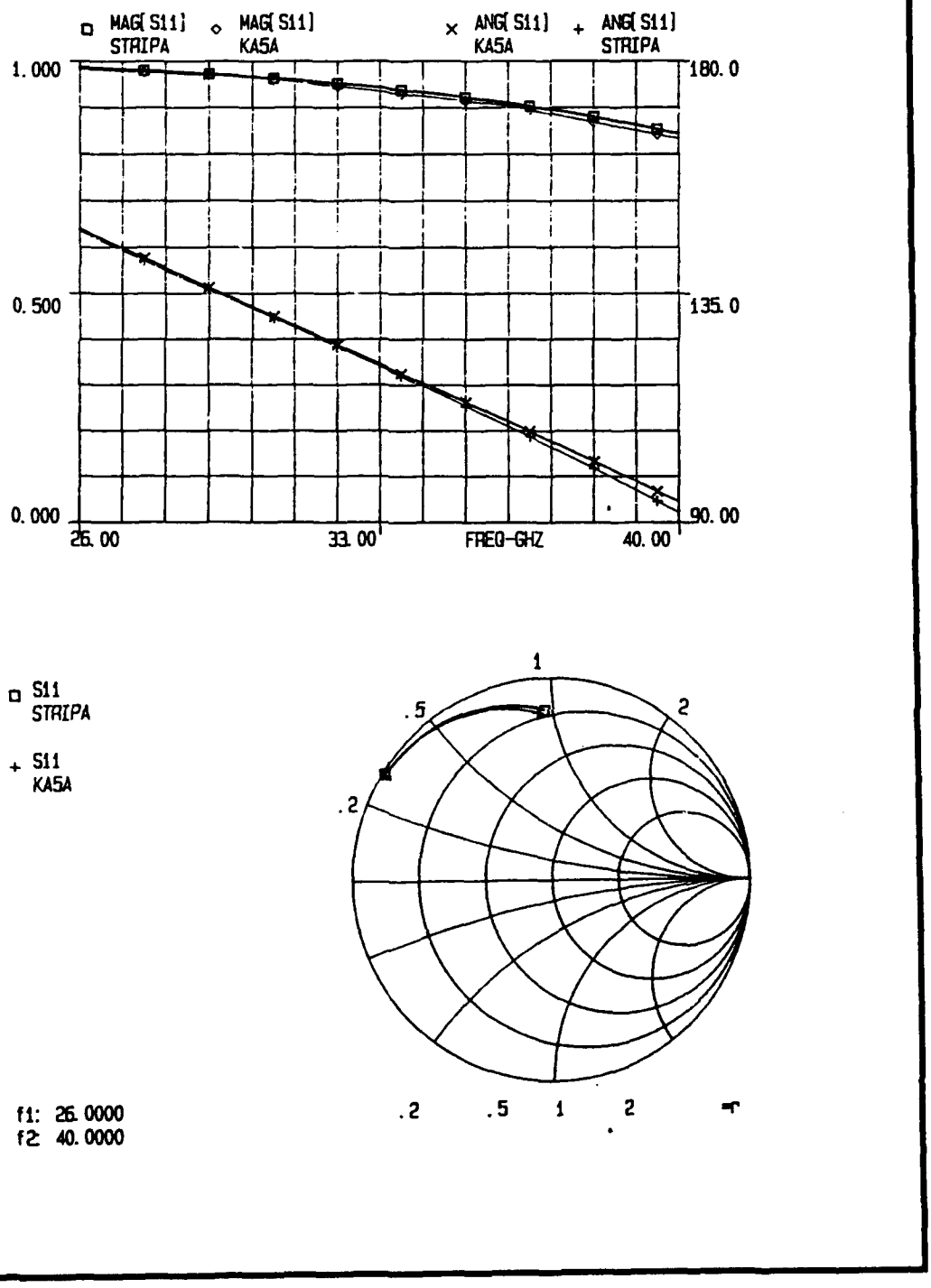


Figure 59. Plots for WR(28), w/b=1, T=2 mm, t=0 mils.

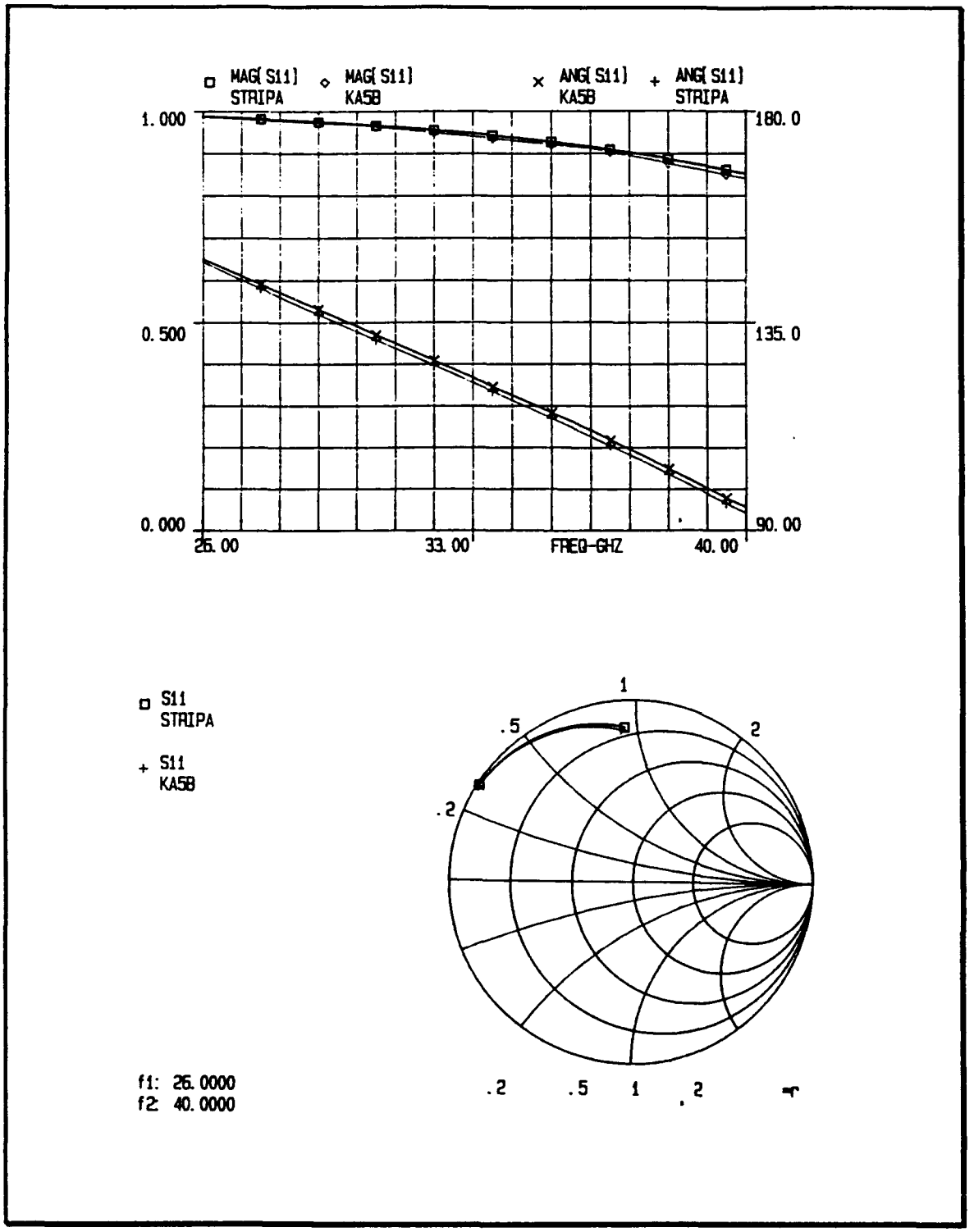


Figure 60. Plots for WR(28), w/b=1, T=2mm, t=1 mils.

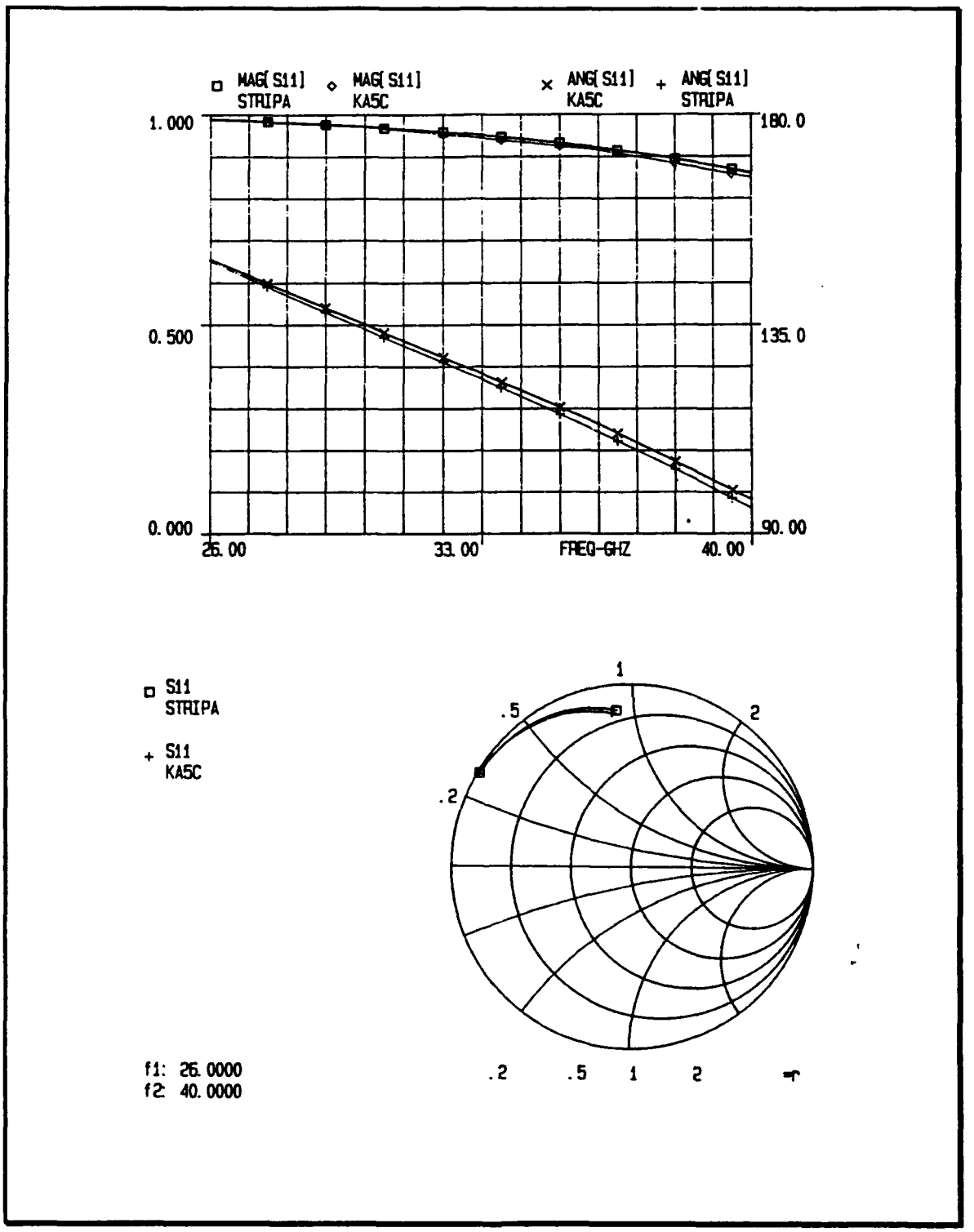


Figure 61. Plots for WR(28), w/b=1, T=2 mm,t=2 mils

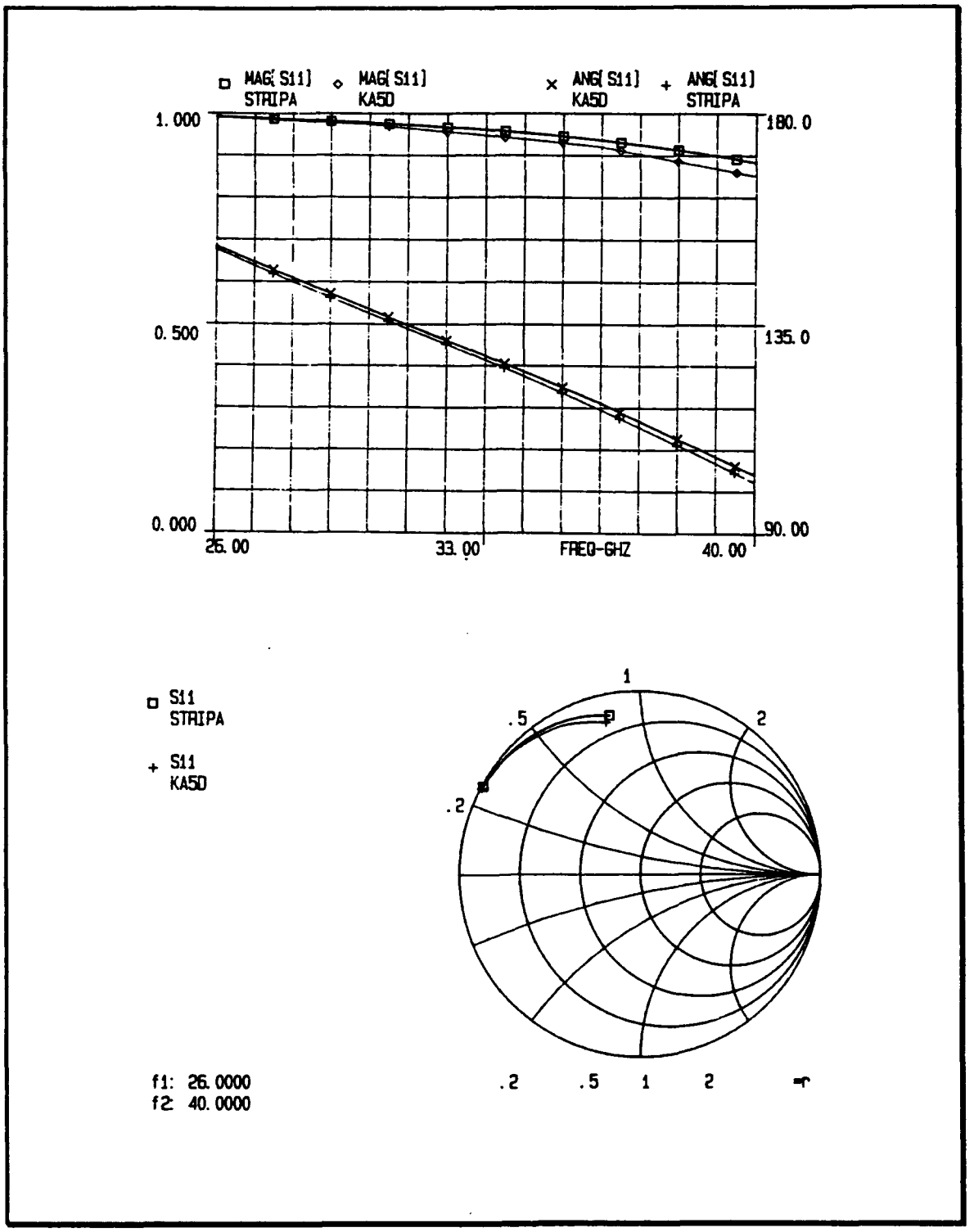


Figure 62. Plots for WR(28), w/b=1, T=2 mm, t=5 mils.

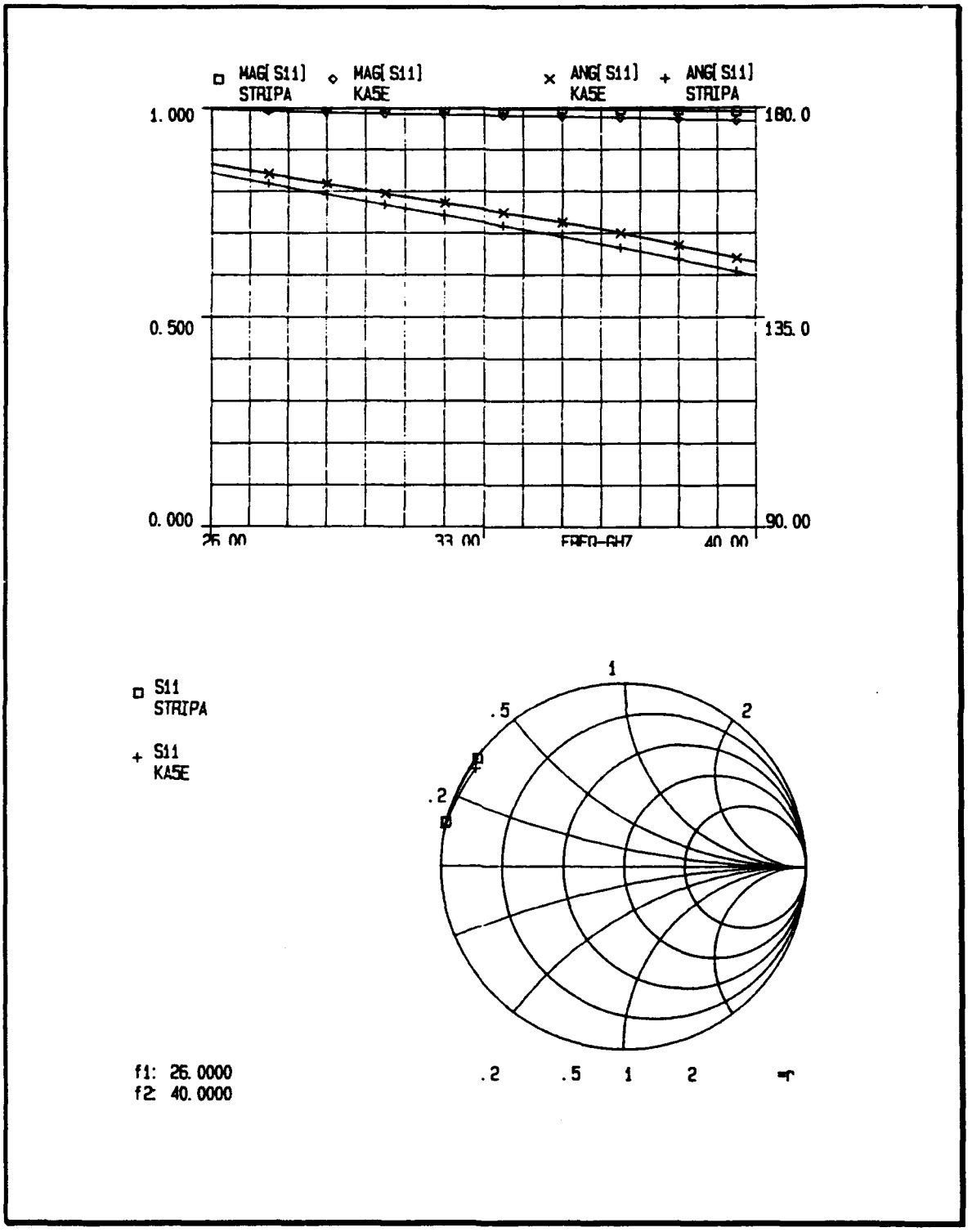


Figure 63. Plots for WR(28), w/b=1, T=2 mm, t=50 mils.

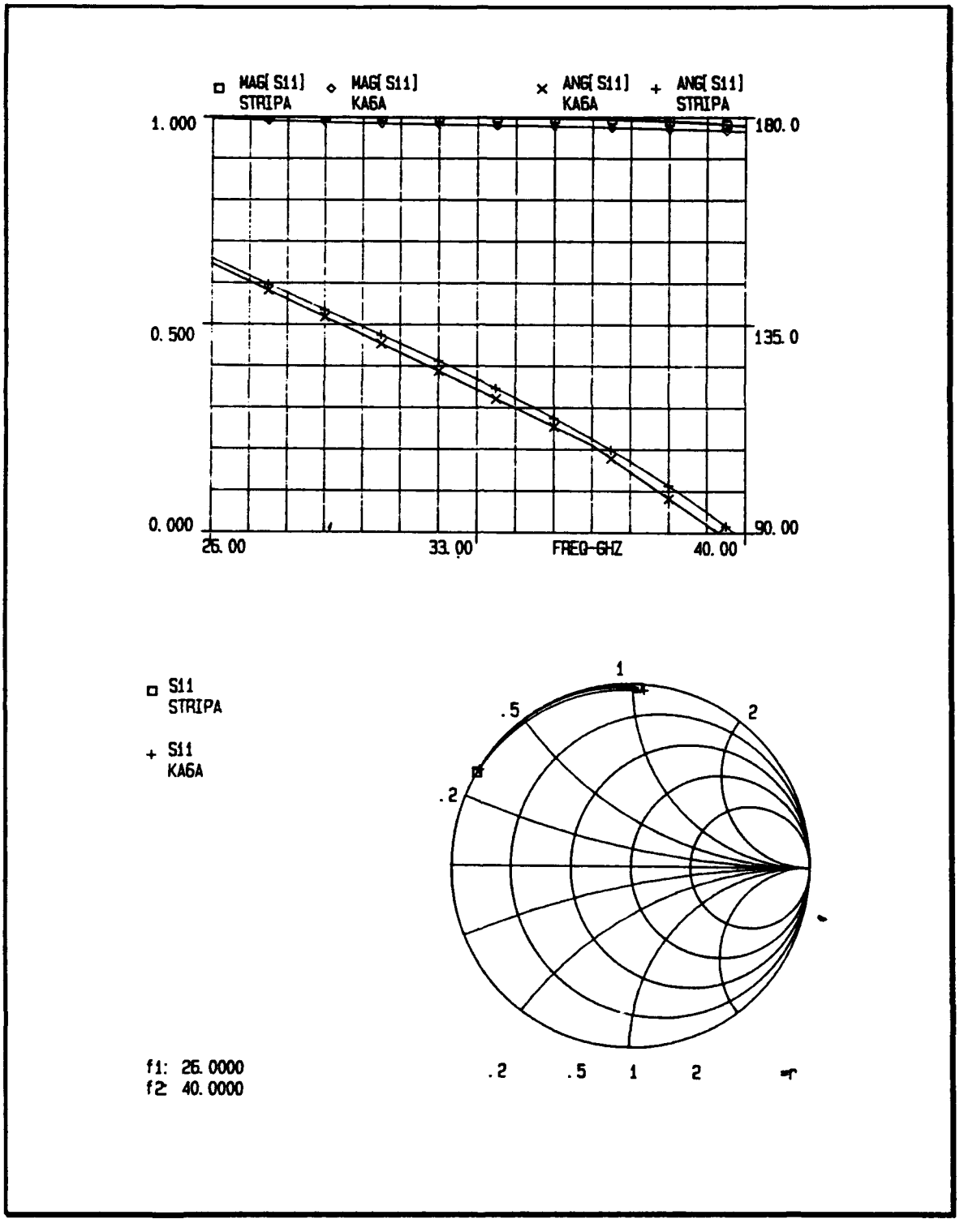


Figure 64. Plots for WR(28), w/b=1, T=5 mm, t=0 mils.

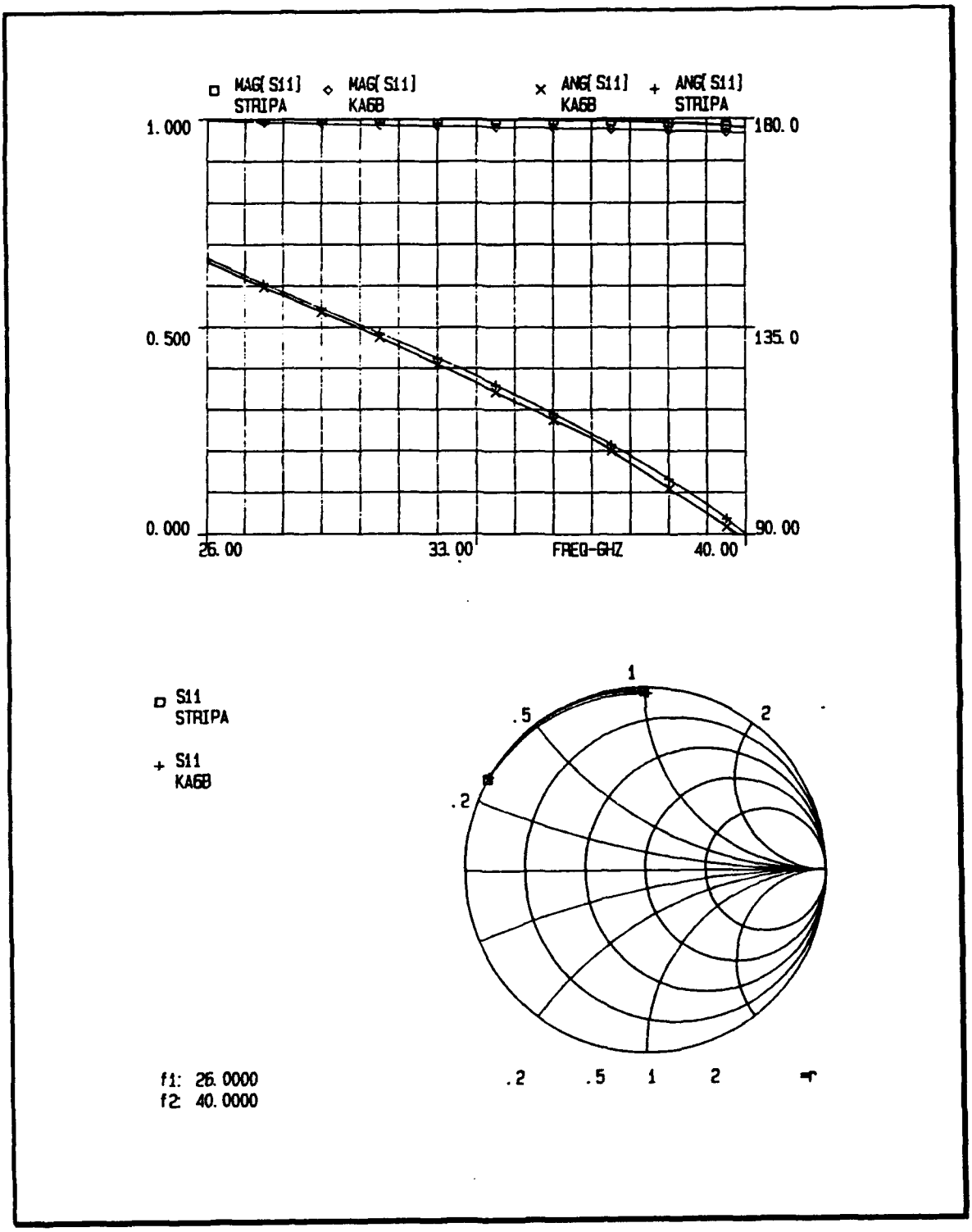


Figure 65. Plots for WR(28), w/b=1, T=5 mm, t=1 mils.

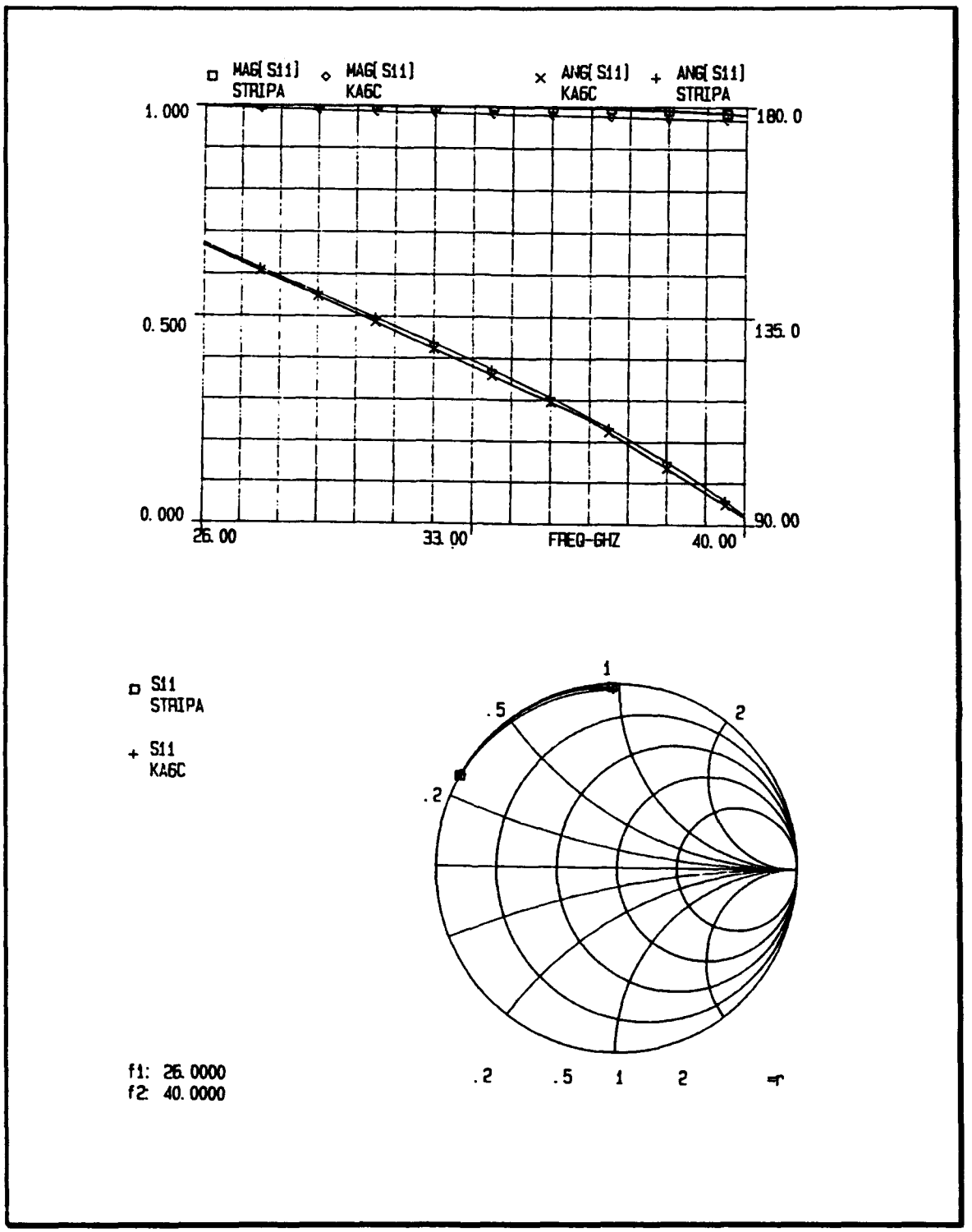


Figure 66. Plots for WR(28), w/b=1, T=5 mm, t=2 mils.

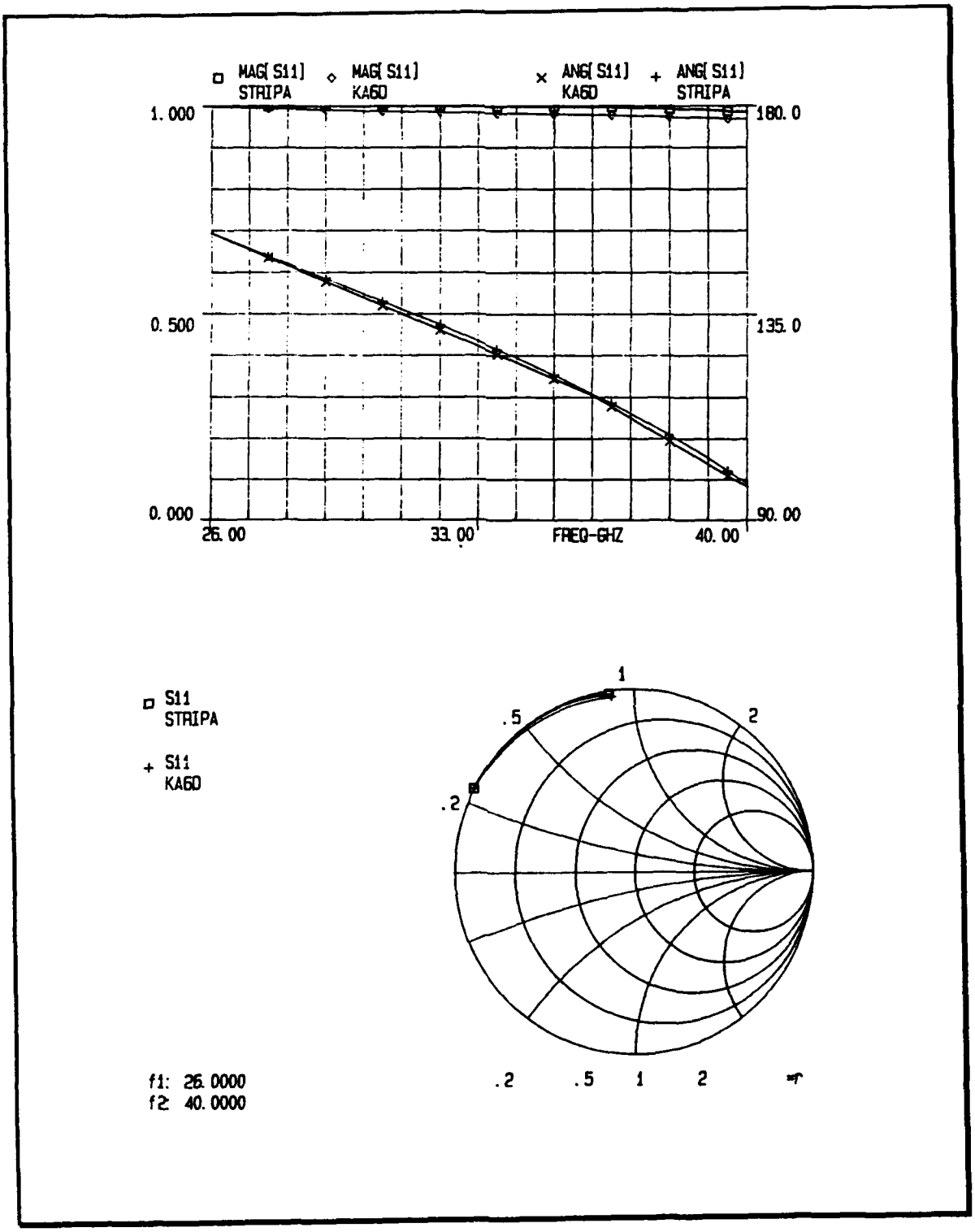


Figure 67. Plots for WR(28), w/b=1, T=5 mm, t=5 mils.

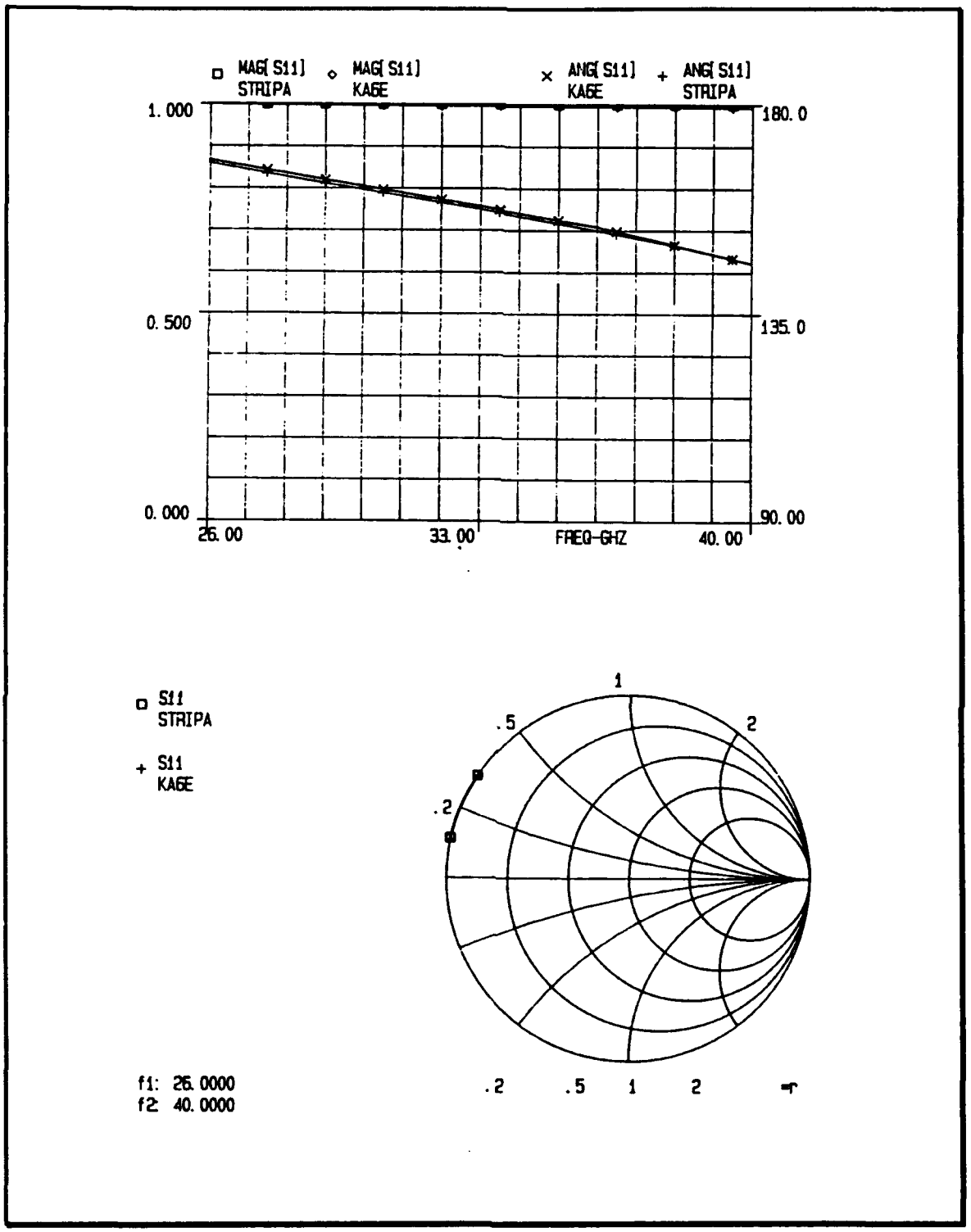


Figure 68. Plots for WR(28), w/b=1, T=5 mm, t=50 mils.

APPENDIX C.

TABLE 10. S-DATA FOR WR(28), w/b=1, T=15 MILS t=0 MILS

Frequency	|S11|	Θ11	|S12|	Θ11
26.10	0.826	139.116	0.563	49.116
28.10	0.764	131.876	0.645	41.876
30.10	0.706	125.705	0.708	35.705
32.10	0.652	120.272	0.758	30.272
34.10	0.601	115.390	0.799	25.390
36.10	0.553	110.937	0.833	20.937
38.10	0.509	106.831	0.860	16.831

TABLE 11. S-DATA FOR WR(28), w/b=1, T=15 MILS, t=0 MILS FROM [REF.10].

Frequency	|S11|	Θ11	|S12|	Θ12
26.10	0.8494	141.7676	0.5277	51.7676
28.10	0.7883	134.39	0.6152	44.1739
30.10	0.7316	128.3203	0.6817	38.3204
32.10	0.6795	122.6251	0.7337	32.6250
34.10	0.6323	117.8790	0.7748	27.8790
36.10	0.5878	114.1348	0.8090	24.1348
38.10	0.5476	110.2852	0.8367	20.2852

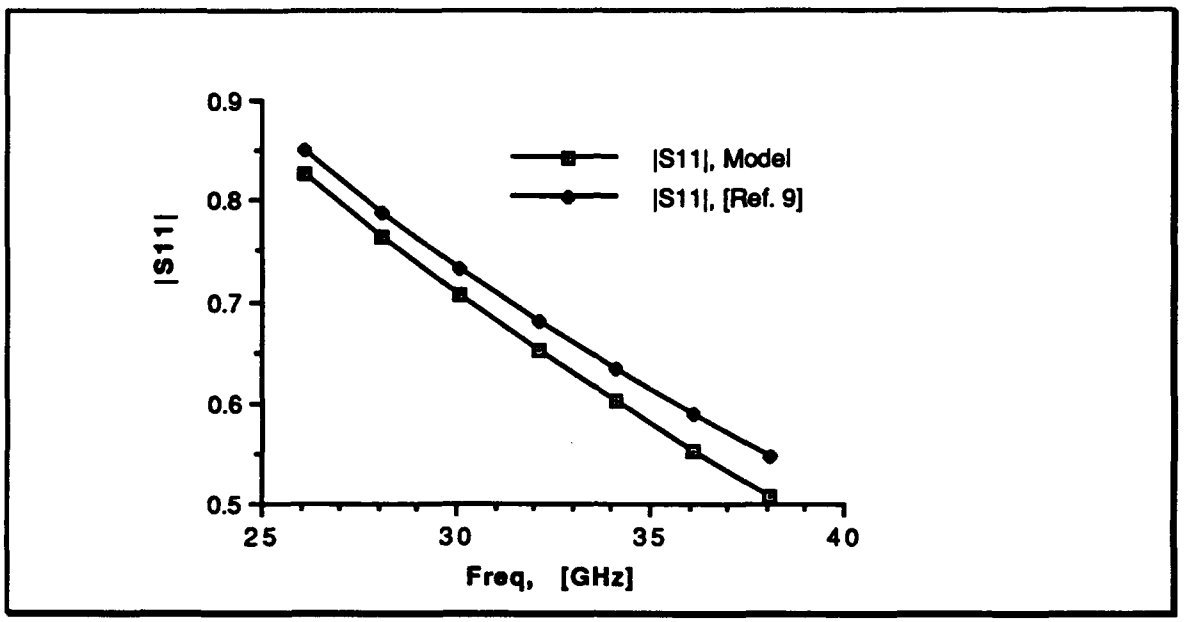


Figure 69. Magnitude for WR(28) with w/b=1, T=15 mils, t=0 mils.

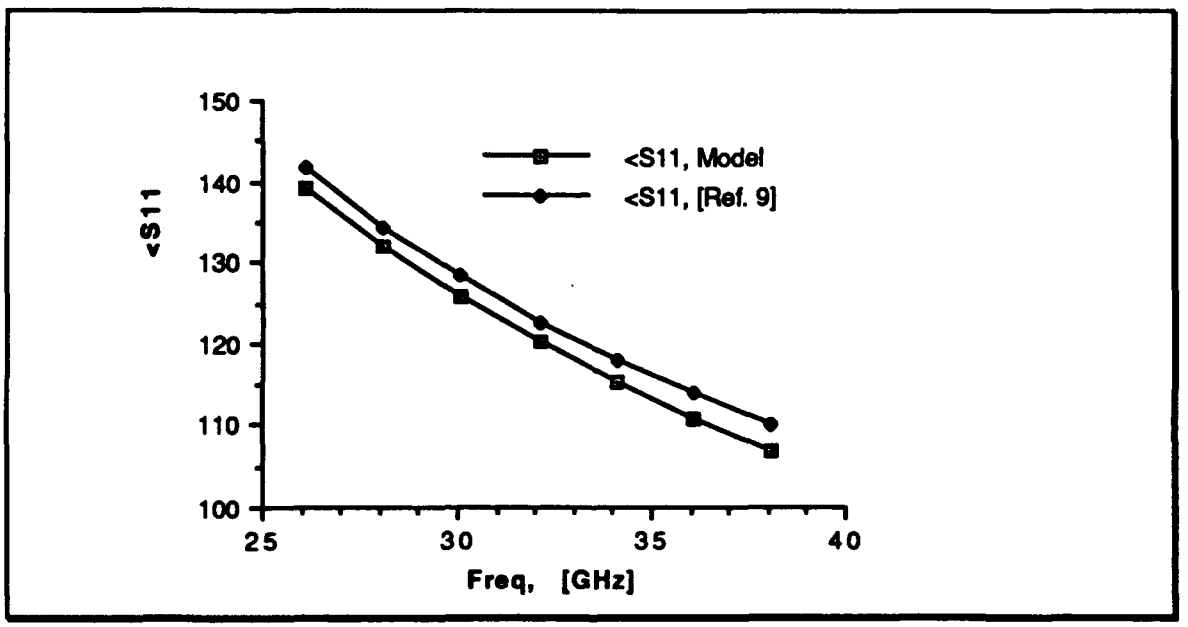


Figure 70. Angle for WR(28) with w/b=1, T=15 mils, t=0 mils.

TABLE 12. S-DATA FOR WR(8), w/b=1, T=30 MILS, t=0 MILS FROM [REF. 9].

Frequency	|S11|	Θ11	|S12|	Θ11
90	0.9956	151.3653	0.0937	61.3653
95	0.9933	145.6700	0.1157	55.6700
100	0.9901	140.0274	0.1404	50.0274
105	0.9862	134.8595	0.1658	44.8594
110	0.9808	130.0079	0.1948	40.0079
115	0.9741	124.0489	0.2263	34.0489
120	0.9653	118.6172	0.2611	28.6172
125	0.9540	112.5001	0.3000	22.5001
130	0.9382	106.5411	0.3461	16.5411
135	0.9184	99.6856	0.3957	9.6856
140	0.8914	92.3555	0.4532	2.3555

TABLE 13. S-DATA FOR WR(8), w/b=1, T=30 MILS, t=0 MILS.

Frequency	|S11|	Θ11	|S12|	Θ12
90	0.995	149.153	0.00998	50.153
95	0.993	143.611	0.1181	53.611
100	0.990	138.230	0.1410	48.23
105	0.986	132.877	0.1667	42.877
110	0.981	127.460	0.1940	37.46
115	0.974	121.907	0.2265	31.907
120	0.966	116.153	0.2585	26.153
125	0.955	110.141	0.2966	20.141
130	0.942	103.814	0.3356	13.814
135	0.924	97.118	0.3823	7.118
140	0.901	90.005	0.4338	0.005

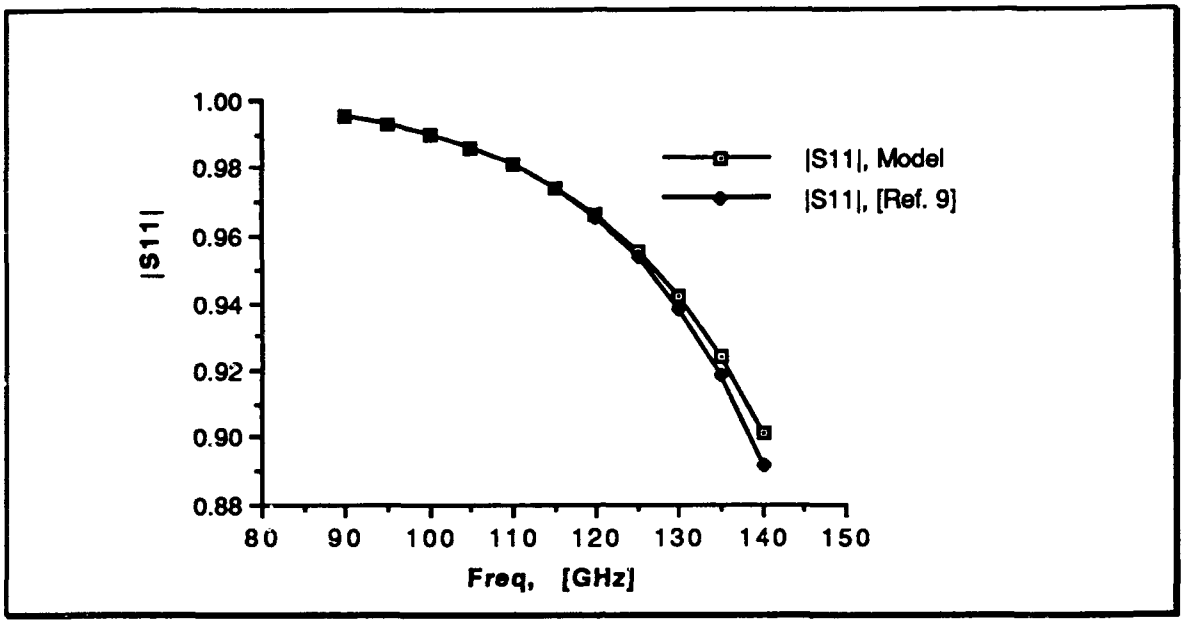


Figure 71. Magnitude for WR(8) with w/b=1, T=30 mils, t=0 mils.

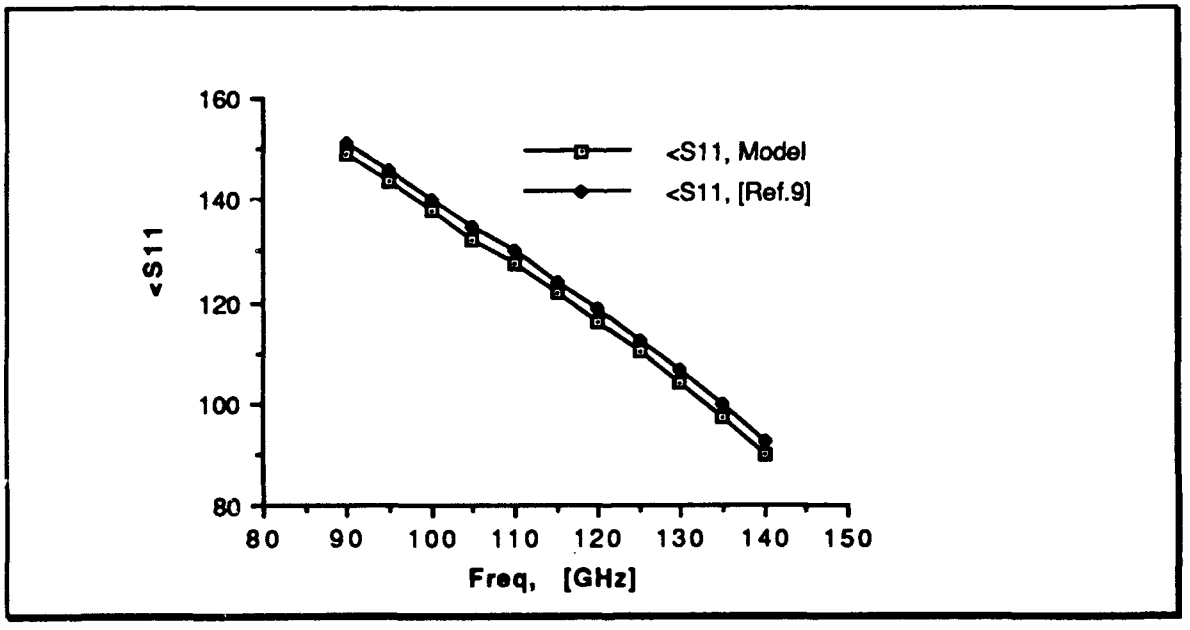


Figure 72. Angle for WR(8) with w/b=1, T=30 mils, t=0 mils.

TABLE 14. WORST ERROR FOR METAL THICKNESS t=0 MILS.

Strip length	S11 (Match) Max Error	S11 (model) Max Error
0.1 mm	9.5%	8%
0.2 mm	9%	6.8%
0.5 mm	3.15%	3.9%
1 mm	0.29%	1%
2 mm	0.84%	1.2%
5 mm	1.2%	1.3%

TABLE 15. WORST ERROR FOR METAL THICKNESS t=1 MILS.

Strip length	S11 (Match) Max Error	S11 (Model) Max Error
0.1 mm	10%	10%
0.2 mm	8.3%	7.1%
0.5 mm	1.9%	3.7%
1 mm	1.3%	0.57%
2 mm	1.54%	1.1%
5 mm	1.34%	1.34%

TABLE 16. WORST ERROR FOR METAL STRIP t=2 MILS.

Strip length	S11(match) Max Error	S11(Model) Max Error
0.1 mm	10%	9.8%
0.2 mm	4.6%	5.6%
0.5 mm	1.21%	2.8%
1 mm	0.56%	0.7%
2 mm	1.29%	1%
5 mm	1.24%	1.3%

TABLE 17. WORST ERROR FOR METAL THICKNESS t=5 MILS.

Strip length	S11(match) Max Error	S11(Model) Max Error
0.1 mm	6.4%	6.3%
0.2 mm	3.2%	1.6%
0.5 mm	0.4%	0.5%
1 mm	1.76%	1.4%
2 mm	2%	2%
5 mm	1.1%	1.6%

TABLE 18. WORST ERROR FOR METAL THICKNESS t=50 MILS.

Strip length	S11(match) Max Error	S11(Model) Max Error
0.1 mm	0.95%	0.5%
0.2 mm	1.6%	1.5%
0.5 mm	2.4%	1.5%
1 mm	1.5%	0.8%
2 mm	2.6%	2%
5 mm	0.6%	0.6%

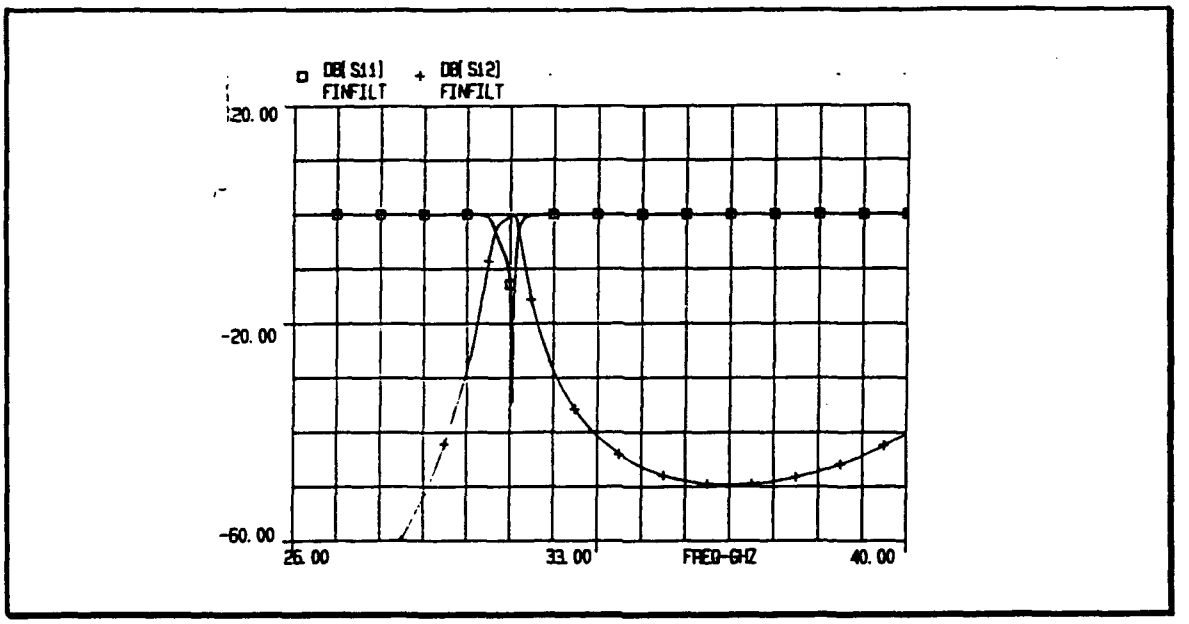


Figure 73. Model response for the Ka band filter with t=0 mils.

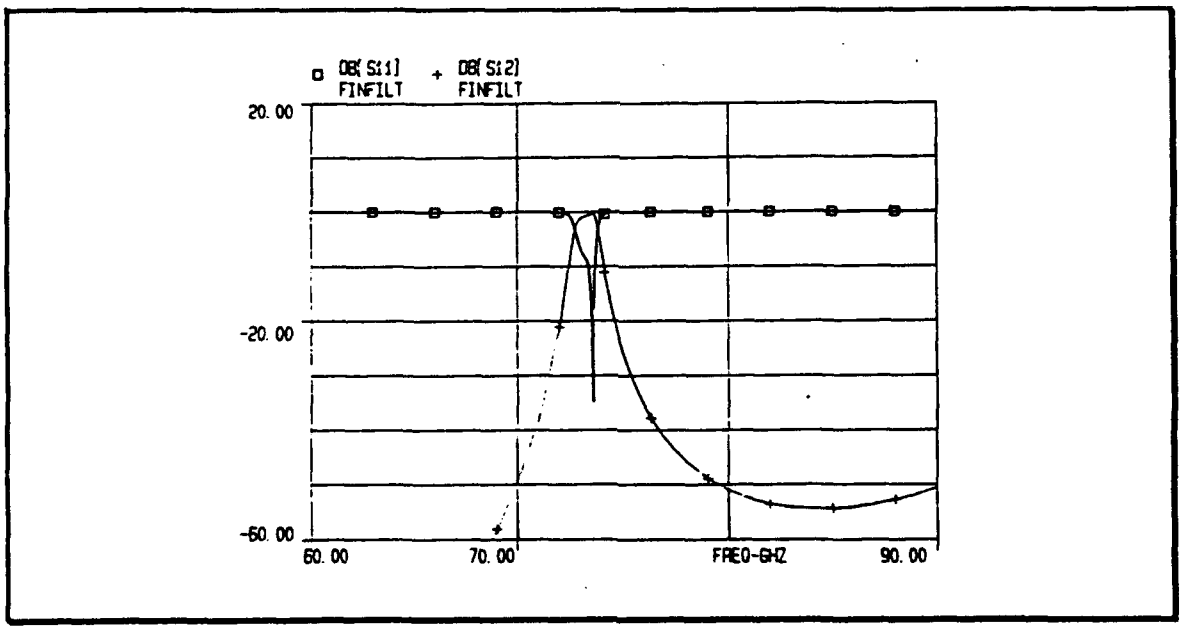


Figure 74. Model response for the E band filter with t=0 mils.

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